Poverty and natural resource management in the Central Highlands of Eritrea

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Bereket Araya

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List of Abbreviations

ARS	Afdeyu Research Station
BEMs	Bio-economic models
CHL	Central Highlands
DAP	Diammonium Phosphate
EHRS	Ethiopian Highlands Reclamation Study
FAO	Food and Agriculture Organization
FFW	Food for Work
GOE	Government of Eritrea
kg	Kilogram
km	Kilometer
MOA	Ministry of Agriculture
MOEM	Ministry of Energy and Mines
NGOs	Non-government organizations
NRM	Natural Resource Management
quintal	100 kilogram
RUSLE	Revised Soil Loss Equation
SSA	Sub-Saharan Africa
SWC	Soil and Water Conservation
TCG	Technical Coefficient Generator
TLU	Tropical Livestock Unit (TLU)
USLE	Universal Soil Loss Equation
ZDE	Zoba Debub East
ZDW	Zoba Debub West
ZM	Zoba Maekel

Chapter 1

Introduction

1.1 Background of the study

Eritrea is one of the poorest countries in Sub-Saharan Africa (SSA) with a population of 4 million of which the majority or 70 percent are engaged in rural and agricultural-based economic activities. It has one of the lowest per capita incomes in the world and high incidence of absolute poverty. Poverty is more pervasive in rural areas where about 66 percent of the poor live. The country also faces a related problem of severe food insecurity both at national and household level. Domestic production of food crops covers between 60 and 70 percent of total food needs, but this can be as low as 10 percent in poor years. The country has also limited financial capacity to cover deficits by commercial imports and thus highly depends on food aid. At the household level, the extent of food insecurity manifests itself in the level of caloric intake and nutritional composition of the typical Eritrean diet, which is below the minimum standard (GOE, 2004a).

In terms of land size, the Central Highlands (CHL) of Eritrea[1] cover about 16 percent of the total land of the country, which is 124,320 km^2 (see Figure 1.1). However, it is one of the few areas where climatic conditions allow rain-fed crop production. As a result of this and the favourable weather conditions, the Central Highlands are home to some 65 percent of the population and an important region in terms of its contribution to food production in the country (World Bank, 1994). Low and erratic rainfall, degraded soils and traditional farming practices that make little use of external inputs has led to very low levels of agricultural productivity even by SSA standards.

Land degradation, particularly soil erosion and deforestation, are the two major environmental problems in Eritrea. The problem of land degradation is particularly acute in the highlands of the country where topography is mountainous and undulating with poor vegetation cover. The relatively high

[1] We use the terms "Central Highlands" or simply the "Highlands of Eritrea" interchangeably to refer to the study area (see Figure 1.1 and Section 5.3).

density of population and centuries of continuous cultivation have also contributed to the problem. It is estimated that 15 – 35 tons of topsoil are eroded per hectare every year. The forest cover of the country has declined from 30 percent of the total land area at the beginning of last century to only 0.8 percent at present (FAO, 1994).

The living conditions of the rural population are adversely affected by the decline in the quantity and quality of natural resources, frequent droughts and war. Agricultural productivity is decreasing with soil erosion and depletion of important nutrients. As many areas in the country are totally devoid of trees, farmers no longer get many of the services they used to get from the forests such as fuelwood, construction materials, shade etc. People have to travel longer distances and spend more time in collecting fuelwood and/or divert to lower quality sources for fuel. Dung and crop residues are used as fuel rather than as fertilizer, and this negatively affects crop yields. Livestock are being underfed due to degradation of grazing land. In general, land degradation is reducing farm income and worsening the quality of life of the rural poor.

1.2 Statement of the problem

Although the environmental problems developing countries are facing are partly due to natural factors such as drought and desertification, most of it is due to poverty-driven human activity. Conditions of high poverty are believed to induce the poor to use their resources in an unsustainable way, both due to inability to invest in natural resource management (NRM) as well as myopic survival strategies that could have detrimental effects on the natural resource base. The decline in these resources in turn deepens their poverty, making the poor both agents and victims of environmental degradation (Dasgupta and Maler, 1994). The implication of such a vicious circle relationship between poverty and environment is that policies that improve the environment will reduce poverty and reducing poverty will have a positive impact on the state of natural resources.

Agricultural intensification, which involves a more efficient use of nutrient application and improved soil and water management, is considered prerequisite to simultaneously enhance rural income and environmental sustainability in areas of high population growth (Lee *et al.,* 2000). The response of rural households to population growth and/or a decline in the availability of resources such as land, water or trees is influenced by economic and institutional factors. Absences of suitable technologies, land tenure systems that do not encourage long-term investments, absence or imperfection of markets for inputs and outputs and inappropriate policy environments often hinder the process of agricultural intensification in developing countries. Despite high levels of population growth, and the resulting diminishing farm size, declining yields resulting from land degradation and acute shortage of fuel wood in the Central Highlands of Eritrea, the pace of agricultural intensification is very slow.

Various policies and programs that provide a range of direct and indirect incentives to farmers to encourage them to adopt new technologies have been pursued in developing countries in the past few decades. In Eritrea as well, the Ministry of Agriculture is making considerable efforts to improve infrastructure (such as roads, dams etc.), to make modern agricultural inputs and implements available in the market at reasonable prices, to train farmers in the use of modern inputs, and to improve farmers' access to credit (GOE 1998). Considerable investments have also been devoted to combating land degradation. Between 1979 and 1992 about USD 116 million of Food for Work (FFW) assistance was allocated for hillside terracing, construction of bunds and tree planting in the country (World Bank, 1994). The government has also been mobilizing highschool students to participate in reforestation and soil conservation programs. Permanent and temporary closure programs designed to rehabilitate degraded native woodlands were initiated in various parts of the country.

Public projects such as those mentioned above and the use of incentives are often justified by divergences between private and social returns to adoption of new technologies. It is argued that some of the benefits from the adoption of some technologies may not accrue to the farmers who incur the cost. Besides, lack of information, capital and credit services in rural areas of developing countries may hinder adoption of technologies even if the technology is profitable to the farmers (Scoones and Toulmin, 1999).

While the above arguments are justified, it is possible that incentives may sometimes be used to promote technologies that are not economically or socially profitable (Enters, 1999; Pandey 2001). Thus a careful assessment of the benefits and costs of various technologies and programs needs to be made before embarking on such expensive public projects. Moreover, despite huge incentives for a long time the rates of adoption of many technologies remain very low in most developing countries. Farmers in some developing countries have even been observed reverting back to their original practices when incentives are discontinued (Shiferaw and Holden, 1998; Sanders *et al.*, 1999). In Eritrea, notwithstanding the efforts of the government, the use of modern inputs and modern agricultural practices remains very low. Although no systematic evaluation of soil and water conservation (SWC) and afforestation programs was made, there are clear indications that the achievements are modest at best. While the administrative records of the Ministry of Agriculture indicate that the cumulative area of plantation establishments between 1979 and 1996 is about 60,000 hectares, FAO (1994) estimates show that the total area under plantation is less than 15,000 hectares. Despite the distribution of free seedlings for decades, individual tree planting in the country is not common.

1.3 Objectives of the study

Farm households' land use and land management decisions have often a simultaneous influence on rural income and the environment. These decisions, in turn, are influenced by various economic, biophysical, institutional and policy environments. Thus a thorough understanding of farm household behaviour is needed to explore if a given technology is to be accepted by farmers and to assess the effect of the technology on rural income and the environment.

The major objectives of this study are, therefore, 1) to comprehend land use and technology decisions by rural households in the Central Highlands of Eritrea, 2) to undertake a quantitative assessment of the impacts of technology change and policies (programs) on rural income and land degradation in various regions of the Central Highlands of Eritrea and 3) to analyse under which socio-economic and biophysical conditions new technologies are likely to be accepted. The specific research questions that are dealt with in this study are:

1. Which factors influence land use and technology choice decisions by rural households and how?
2. How can we assess the linkages between household decisions, rural income and indicators of sustainability?
3. What are the effects of various new technologies on rural income and land degradation in various regions of the Highlands of Eritrea?
4. How do incentives for mobilization of community labour for soil conservation and reforestation hamper private initiatives on soil conservation and tree planting activities?

1.4 Methodology of the study

To achieve the objectives and to answer the research questions we executed a thorough study of the farming systems in three subregions of the Central Highlands of Eritrea. These subregions differ in terms of population density, agricultural potential and market access. For each sub region, rural households' resource endowments, the economic, social and institutional environments that influence their livelihood strategies, as well as the major constraints they face have been explored using structured questionnaires and informal discussions with farmers, village elders, community leaders and agricultural experts. The extents to which new technologies and modern farming practices are introduced in the various regions of the Central Highlands were also assessed. Farmers' perceptions about the risk of land degradation on their farms, as well as their perceptions about the trends of crop yields and the major reasons for such changes were also investigated.

Operations Research models are useful tools of analysis to simulate and analyse farmers' strategies under actual and potential technologies and policy conditions. Mathematical modelling can play an important role in simultaneously studying the large number of interrelated factors that influence the decisions of rural households (Schweigman, 2005). A village-level mathematical model that captures the interactions between biophysical (environmental) and socio-economic factors is developed which will be used to assess the impact of technological changes and policy incentives (Chapter six). Since consumption and production decisions of the rural households in rural areas of the Central Highlands are closely interrelated, the model considers these decisions simultaneously (see Chapter four). As biophysical and socio-economic conditions vary considerably in different parts of the highlands, different types of technologies and interventions may have different impacts on income and land degradation. As a result, farmers' willingness and ability to adopt these technologies may also differ among the different regions of the highlands of Eritrea. Thus, the mathematical model was applied to three villages representing the three subregions in the Central Highlands.

Quantitative assessment of technological changes and policy interventions on rural income and the environment requires inputs from socio-economic and biophysical sciences. The socio-economic data used in this study comes from our field studies and from studies by ministries, international organizations and regional studies. The quantification of technical data coming from other sciences (such crop yields, erosion and nutrient losses) falls outside the scope of this study. Nevertheless, as these data are key components in our model, considerable effort is made to obtain realistic parameters. The major part of these technical data is generated by making use of biophysical simulation models developed in international research institutions. The Technical Coefficient Generator (TCG) developed for the highlands of Ethiopia (Hengsdijk, 2003) is the most important source for these data. Some inputs of the the TCG are modified to reflect the biophysical conditions (e.g. altitude) of the Highlands of Eritrea. The parameters obtained using biophysical simulation models are compared with empirical evidences from agricultural research stations, and field observations and were sometimes adjusted to reflect the real situation (see Chapter seven).

1.5 Organization of the study

The thesis consists of ten chapters. Chapter one presents the background of the study, the main research questions and the objectives of the study.

Chapter two first presents a brief description of the performance of the agricultural sector in Africa and the underlying reasons for the low performance of the sector in the continent. The nature and processes of agricultural intensification, as well as the relationships between population growth, poverty and land tenure on the one hand and agricultural intensification on the other are discussed and some empirical evidences are presented.

Chapter three provides a description of the current state of the agricultural, energy and forestry sectors in Eritrea and discusses the linkages between those sectors and land degradation. It highlights the factors that contribute to the low and variable levels of crop and livestock production. It also discusses the nature and extent of land degradation in the country and the major factors that contribute to the problem.

Chapter four presents the theoretical background for the mathematical model developed in Chapter six and makes the case for the choice of the type of model. The structure of the model and the links between rural households' resource endowments, household objectives, as well as the economic and biophysical circumstances that influence their decisions are illustrated. The major components of the model are also briefly described.

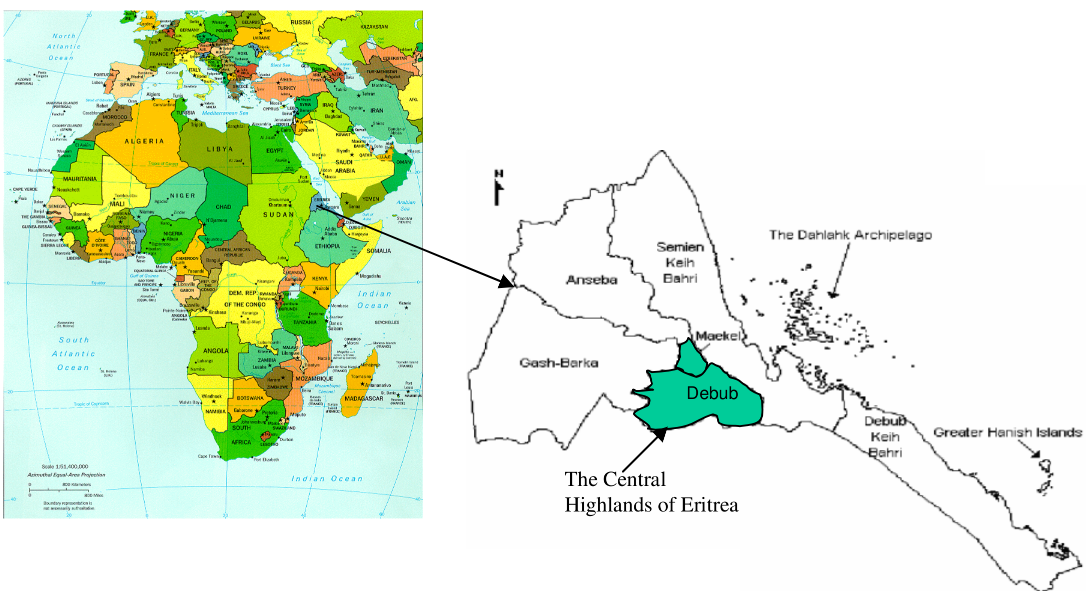
Chapter five describes the study area (and study villages) and presents the methods of collecting primary data. The results of the fieldwork which include household endowments of land labour and livestock resources, farming practices and other economic activities of rural households, as well as institutional arrangements and cultural and religious factors that influence household decisions are explored. Farmers' perceptions about the impacts of some technologies on crop yields as well as the major constraints to adopt those technologies are also explored.

Chapter six presents the mathematical model in detail and Chapter seven deals with the estimation of model parameters. Particular emphasis is given in Chapter seven to the estimation of crop yields and soil losses as a function of fertilizer use and soil conservation. The Technical Coefficient Generator, which was used to estimate the above parameters, is described in detail. Empirical evidences from research stations in Eritrea were also analysed to check the validity of the data obtained from simulation models.

Chapter eight presents the results of the base model. The model was run for the three study villages separately. The results for the villages were compared to current practices to test the validity of the model. Possible reasons for divergences between simulated results and current practices were carefully discussed and implications for improvements and policy suggestions are explored. The results of the three villages were also compared with each other to give insights on the impacts of biophysical and socio-economic differences.

In Chapter nine the model is applied to assess impacts of various technologies and public projects on rural income, on land use, and on soil and nitrogen losses. This is done for each village separately. The results show the biophysical and socio-economic conditions under which each technology or intervention will be appropriate. Chapter ten presents a summary of the thesis and highlights the key findings and conclusions.

Figure 1.1 The study area



Chapter 2

Agricultural Intensification, Agricultural Productivity and Land Degradation in Africa

2.1 Introduction

Extreme poverty is the general characteristic of most countries in sub-Sahara Africa (SSA). Low levels of per capita income, low levels of literacy, malnutrition and high levels of infant mortality are the rules rather than exceptions in this region. Despite concerted efforts by the governments of these countries and the international community, these dimensions of poverty and deprivations are still increasing in many parts of SSA (IFAD, 2002).

In addition to the high levels of poverty, Africa also suffers from a vast inequality in income. Inequality is particularly notable between the rural and urban areas of the continent. More than 80 percent of the extremely poor in SSA are found in the rural areas and about 85 percent of the poor depend on agriculture for their livelihoods. Thus, while high and sustained levels of economic growth may be helpful to reducing the number of poor people, in economies characterized by high levels of inequality, economic growth alone may not be sufficient to eliminate poverty. It is necessary to focus efforts on policies that will have direct impact on the poor.

The poor people in the rural areas rely heavily on their environment for most of their needs and are affected by the deterioration in the quality and quantity of these resources. The condition of the majority of the rural poor in many developing countries is a vicious circle between environmental degradation and poverty. Poverty influences farmers' ability and willingness to control land degradation and land degradation leads to lower agricultural productivity and, therefore, more poverty (WCED, 1987, 1993; Dasgupta, 1992; Barbier, 1999). The relationship between agricultural growth, poverty alleviation and sustainable land management is, however, complex and a subject of much controversy. The links between these issues are conditioned by various factors including demographic, economic, institutional, and policy conditions. It is, thus, essential to find policies, technologies and institutions that reduce land degradation and poverty at the same time.

This chapter is organized as follows. In the following section we will briefly discuss the performance of agriculture in Africa in the past few decades. Next we will discuss the nature and extent of land degradation in the continent. Section 3.4 will discuss the process of agricultural intensification and the reasons why African farmers fail to intensify (invest on) their agriculture. Finally we will briefly discuss the theoretical links between population growth, poverty and land tenure on the one hand and land degradation on the other.

2.2 Performance of agriculture in Africa

Most countries in Africa heavily depend on agriculture that is dominated by subsistence production. The performance of Agricultural sector in SSA was the worst in the third world countries in the last quarter of the last century. Agriculture is still based on traditional methods of production with little use of modern inputs. The low level of productivity in this sector is exhibited in the fact that while the sector employs about 67 percent of labour force in Africa, it contributes for only 17 percent of the total gross domestic product (World Bank, 2000). The majority of the farmers are smallholders cultivating 0.5 to 2 hectares of impoverished lands highly susceptible to erosion with little external inputs. Thus crop yields in Africa are extremely low – about 33 percent and 50 percent of the yields in Asia and South America respectively. Africa is also the only region where average food production per person has been declining over the past 40 years (Sanders *et al.,* 1996). In addition, high degree of production and price variability, low proportion of irrigated land, low levels of fertilizer use and high dependence on primary exports are common features of African agriculture. Table 2.1 shows that SSA lags far behind most regions in terms of agricultural indicators such as proportion of irrigated land, per capita cereal production, crop yield and fertilizer use.

Table 2.1 Agricultural indicators by region

	Africa	Sub-Sahara Africa	Near east and North Africa	South Asia	East Asia and Pacific	Latin America and Caribbean	Middle income countries	High income countries	World
Proportion of arable land irrigated	7.0	3.8	28.7	39.3	31.9	11.6	19.9	11.9	20.0
Per capita cereal production kg/year	147	128	128	224	336	259	339	746	349
Cereal yield kg/ha	1225	986	1963	2308	4278	2795	2390	4002	2067
Fertilizer use kg/ha	22	9	69	109	241	85	111	125	100

Source: FAOSTAT

Poor resource endowments and adverse policies that continued for a long period are identified as the major causes of low and declining performance of the agricultural sector in SSA. Continuing environmental degradation, high population growth, low levels of investment in agricultural infrastructure also aggravate the resource limitation of African agriculture (Sanders *et al.,* 1996; Binswanger and Townsend, 2000; Ehui and Pender, 2003).

Most soils in SSA are inherently poor with low organic content. They tend to drain poorly and are easily susceptible to both wind and water erosion (Wong *et al.,* 1991; Weight and Kelly (1998) cited in Nubukpo and Galiba, 1999). Weight and Kelly (1998) identify four primary soil types in SSA, each with different implications for restoring soil fertility. Fifty seven percent of the total land area was classified as marginally suitable for cultivation with soils characterized by limited organic matter and water retention capacity and 28 percent is low to medium potential land, which is very vulnerable to a decline in organic matter and fertility when few inputs are applied.

Low and poorly distributed rainfall is another major bottleneck for agricultural development in large areas of SSA. Much of Africa is too dry for the new high-yielding varieties that worked so well in Asia. Average rainfall in the dry semi-arid areas of SSA is less than 700 mm/year[2]. The rainy season is also very short: 90-100 days and periods of more than 10 days without rainfall are frequent. The region is also characterized by high temperature that accelerates the degradation of organic matter, which, in turn, reduces the water holding capacity of the soils and makes them deficient in nitrogen and phosphorus. Drought-resistant crops such as millet and sorghum dominate this region (Marter and Gordon, 1996; UNCTD, 1998).

Pricing and exchange rate policies in many SSA countries as well as high direct and indirect taxes on agriculture also led to loss of competitiveness of the agricultural sector and discouraged investment in agriculture and soil conservation measures. Public investment in rural roads, irrigation structures and other rural services are also very low. Agricultural marketing and input supply systems are often dominated by highly unreliable and inefficient public sector. As a result of poor infrastructure and poorly developed input markets, key inputs are not available at the right time and place. As a result of these constraints agriculture in SSA makes use of little external inputs and remains mainly subsistence oriented (Sanders *et al.,* 1996; Binswanger and Townsend, 2000; Pender *et al.,* 2003).

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[2]There is a wide range in the definition of semi-arid areas in the literature. See Sanders *et a*l. (1996) for a brief discussion of these definitions.

2.3 Land degradation

Land degradation in Africa is a serious problem with a considerable impact on the economies of many countries in the continent. A study by Oldeman *et al.* (1992) shows that about 25 percent of the world's degraded lands is located in Africa. It is estimated that 65 percent of Africa's agricultural land is degraded because of water and soil erosion and/or chemical and physical degradation. In addition, 31 percent of the pasturelands and 19 percent of the forests and woodlands in Africa are classified as degraded (Table 2.2). Forest and woodland areas in the continent have decreased by 2 percent in the last 15 years while croplands increased by more than 10 percent (Barbier, 1999).

Table 2.2 Global estimates of soil degradation, by region and land use

	Agricultural land			**Permanent pasture**			**Forests**			**All used land**	
Region	**Total**	**Degr.**	**%**	**Total**	**Degr.**	**%**	**Total**	**Degr.**	**%**	**Degr. %**	**Seriously degr.%**
	millions of hectares			millions of hectares			millions of hectares				
Africa	187	121	65	793	243	31	683	130	19	30	19
Asia	536	206	38	978	197	20	1273	344	27	27	16
South America	142	64	45	478	68	14	896	112	13	16	9
Central America	38	28	74	94	10	11	66	25	38	32	31
N.America	236	63	26	274	29	11	621	4	1	9	7
Europe	287	72	25	156	54	35	353	92	26	27	20
Oceania	49	8	16	439	84	19	156	12	8	17	1
World	1475	562	38	3212	685	21	4048	719	18	23	14

Source: Scherr (1999).

Nutrient depletion is more widely found and is of more serious concern to food security in SSA than in any other part of the world (Smaling, 1993; Cleaver and Schreiber, 1994). Soil fertility depletion is considered as the main biophysical limiting factor for raising per capita food production for most of small African farmers. Some authors maintain even in the Sahelian region, availability of nutrients is a more important constraint than water supply (Penning de Vries and Djiteye, 1982; Sanchez *et al.,* 1997). Stoorvogel and Smaling (1990) quantified nutrient depletion at the national and sub continental scale for most countries in SSA. They showed that nutrient balances are only partially compensated for by natural and man-made inputs and that the annual NPK balances are negative for SSA. The average annual nutrient balance for the region for the period 1983 – 2000 was estimated to be minus 22-26 kg N, 6-7 kg P, and 18-23 kg K per hectare. If nutrient balances on only actual harvested land are considered, i.e., without fallow and fallow inputs, nutrient depletion rates may be double the above figures (Drechsel *et al.,* 2001).

When no external inputs are used, long periods of fallow are required to replenish nutrients taken up by crops. Even assuming much higher nutrient inputs from fallow than current estimates, Drechsel *et al.* (2001) argue that only 20 percent of the arable land can be cultivated each year for a sustainable land management, which is considerably lower than the FAO estimate of 60 percent of the arable land actually cultivated each year. This is practically impossible given the current and increasing population pressure in SSA.

Overgrazing, expansion of agricultural lands and lack of external inputs are the major causes of land degradation in the continent. This is because many African farmers and pastoralists respond to declining land productivity by abandoning existing degraded land and moving to new land (Barbier, 1999). Farmers in SSA did not sufficiently improve their land management practices to the conditions of continuous cultivation and shorter fallow periods, which were caused by increasing population pressure. Irrigated area and the adoption of inorganic fertilizers and other new technologies such as high-yielding varieties are still very low. As a result crop yields in the region in the last few decades were stagnant or even declined. In contrast, irrigation and the use of inorganic fertilizers and other new technologies in Asia have dramatically increased in the last three decades of the last century resulting in more than 80 percent increase in crop yield (Sanders *et al.,* 1996).

A number of studies have been undertaken to estimate the economic costs of soil erosion in terms of lost agricultural production. Countries like Zimbabwe, Ghana and Ethiopia were found to be losing five to nine percent of their agricultural output every year due to land degradation (Bojo, 1996; Barbier, 1999). Barbier (1999) suggests that the loss can even be higher because the estimates refer only to the loss of few crops whereas the agricultural output refers to the value added in crop production and livestock, forestry, hunting and fisheries.

The decline in land productivity is further aggravated by the removal of crop residues and animal manure, which were traditionally important means of nutrient recycling. A study by Ethiopian Forestry Action Program (EFAP, 1992), for example, estimates that the loss of productive croplands and grazing lands from soil erosion in the Ethiopian highlands between 1985-2010 at more than 10,000 sq. km and 3000 sq. km respectively. The study also indicates that the loss of production attributable to the removal of crop residues and dung exceeds soil erosion-induced losses by a factor of 35 to 80 percent. Similar findings were also reported for Eritrea (see Section 3.4).

2.4 Agricultural intensification

Agricultural intensification has been defined as the use of an "increased average inputs of labour or capital on smallholding, either cultivated land alone or on cultivated and grazing land, for the purpose of increasing the value of output per ha" (Tiffen *et al.,* 1994: 29). For agricultural intensification to occur, an increased demand for output or a fall in the availability of key factors such as land, labour or water is needed. Demand for output may increase due to an increase in population, in-migration of people, expansion of markets and increased income. However, while the above conditions are necessary for agricultural intensification to take place, they are not sufficient. We will discuss the theoretical debate on the relationship between population growth and agricultural intensification later in this section. We will first discuss briefly the nature and processes of agricultural intensification.

The nature and processes of agricultural intensification

The process of agricultural intensification may take different forms, which may have different impacts on livelihoods of the rural people and on the environment. These changes include expansion of agricultural land, intensification of labour per unit of land using traditional methods (shortening of fallow cycles), adoption of more labour-intensive methods of production, labour-intensive investment in land (e.g., soil and water conservation structures), adoption of capital-intensive methods, change in product mix, migration and a change in household fertility decisions (Carswell, 1997; Pender, 1999).

Reardon *et al*. (1999) distinguish between sustainable and unsustainable types of agricultural intensification. They appraise the sustainability of agricultural intensification by the following two criteria:

- An environmental criterion: the technology protects or enhances the farm resource base and thus maintains or improves land productivity; and
- An economic criterion: the technology meets the farmer's production goals and is profitable.

They differentiate between "capital-led intensification" and "labour-led intensification". While the latter, also termed as "capital-deficient intensification", refers to intensification that involves excessive dependence on labour as a variable input to production, the former refers to intensification based on substantial use of non-labour variable inputs that enhance soil fertility (such as inorganic fertilizers) and quasi-fixed capital, particularly land and water conservation infrastructure that increase labour productivity.

"Labour-led agricultural intensification" strategy, which makes little use of chemical fertilizer and other chemicals and emphasizes the use of organic matter and land conservation structures, is considered less sustainable from the viewpoint of the two sustainability criteria stated above. It is argued that given the increasing cropping intensity (due to the declining fallow periods) and declining number of livestock, sufficient manure is not available to substitute inorganic fertilizer. Similar observations were also made in the West African semi-arid tropics, that the amount of manure and compost produced in the farm is not sufficient to replace the major nutrients mined from the soil by crop production (Nagy *et al.,* 1988; Reardon *et al.,* 1999). Moreover, labour-led intensification is not sufficiently productive to meet the needs of the fast growing population. It has also been argued that while rural population in Africa is growing at about three percent per year, Low External Input Sustainable Agriculture (LEISA) has the potential of increasing output by only one percent per year. This will lead to soil mining and yield decline in the long run (Sanders *et al.,* 1996). Thus capital-deficient intensification meets neither the economic or economic criteria required for a sustainable agriculture.

Population growth and agricultural intensification

The conceptual debates surrounding agricultural intensification often set in the context of population environment debate. The relationship between population growth, and land degradation has been a subject of debate for a long time. Malthus (1798) argued that while population grows exponentially, production, due to diminishing returns, increases only arithmetically, leading to a decline in per capita output. As population increases, the per capita area of arable and grazing land decreases, and cultivation extends into marginal lands leading to a lower per capita income. Land already cultivated is cultivated more intensively. The increased demand for cultivable land, firewood and construction materials and an increase in the supply of labour that clear trees leads to environmental deterioration.

In contrast to the Malthusian view, others saw population pressure as the major stimulus for intensification. The theory of induced innovation states that reductions in the availability of a resource or an increase in demand for goods will force people to develop and adopt new technologies, which offset the decline in the available land (Boserup, 1965; 1981). In other words, the development and dissemination of new technologies and institutions is directed by relative factor scarcity, as reflected in market prices. While the change in relative prices is the major factor that leads to an endogenous agricultural intensification, the exogenous factors that cause a change in relative prices may be increased population pressure, increased access to markets (which may result from the development of roads and other infrastructure) and/or government policies (Ruttan and Thirtle, 1989; Ruttan and Hayami, 1990; Binswanger and McIntire, 1997).

Others argue that increased demand for goods and services resulting from population growth or a decline in the availability of key factors such as land, labour or water are necessary but not sufficient conditions for agricultural intensification. An endogenous intensification by farmers often fails to take place due to absence or imperfection of the markets for inputs and outputs, institutional arrangements concerning land rights, policy environments that discourage investment on land improvement, absence of suitable technologies and poverty. Farmers may lack the willingness and/or ability to adopt technologies that enhance land productivity and maintain the quality of their land that endogenous investments that are predicted by the theory of induced innovation may not take place or, if they occur, not necessarily occur at the right time and extent (Reardon and Vosti, 1995; Shiferaw and Holden, 1998).

The empirical evidences on the relationship between population growth, agricultural intensification and land degradation are mixed. Several studies have shown that farmers in developing countries responded to increasing population density by fostering technical and social changes, which helped to avoid Malthusian outcomes of declining productivity and land degradation (Pingali *et al.,* 1987; Tiffen *et al.,* 1994; Arnold and Dewees, 1995). For example, despite a five-fold increase in population between the 1930s and 1990s in the Machakos district of Kenya, a comparison of agricultural development and land management in the two periods showed no signs of environmental and economic catastrophes (such as land abandonment and widespread deforestation) in the region. In fact, agricultural output per head increased three fold and the main indicators of land resource management have shown substantial improvements (English *et al*, 1994; Tiffen, 1994). Scherr (1995) also attributed high interests in agroforestry in western Kenya in the 1980s to the rapidly expanding markets for tree products in that area. Godoy (1992) provides 21 regional examples of farmers in Africa, Asia and Latin America who responded to high forest product prices by planting trees. Patel *et al.* (1995) examined the impact of increased population density and land subdivision on tree planting using data from small holders in Tanzania and Kenya. They found that as population density increases, the observed decline in tree cover would reverse and begin to improve. Thus they concluded that the decline in tree cover in those countries was one side of a U-shape relationship between population density and land degradation rather than a secular trend of environmental degradation.

However, others have argued that agricultural intensification does not necessarily follow population growth (Binswanger and Ruttan, 1978; Turner *et al.,* 1993). Despite high population growth, adoption of new technologies remains low in Africa resulting in declining yields and deteriorating environments. Blaikie and Brookfield (1987) warn that despite its historical validity Boserup's argument may not necessarily hold for today's developing countries. They underline that over-exploitation of land, overgrazing of pasture, man-made erosion and deforestation are common phenomena in areas of high population pressure. Pingali *et al.* (1988) maintain that endogenous technical changes by farmers in response to population growth are sufficient to support slow and steady population growth but not rapidly rising population. Even Tiffen *et al.*'s findings of successful agricultural intensification in Machakos district were challenged in that many people in the area were experiencing deteriorating livelihoods (Murton, 1997). Murton argues that although in the early stages of population growth, labour-intensive path of intensification had positive impacts on livelihoods and the environment, at later stages, farmers' lack of access to capital has forced them to proceed along the pathways of declining yields and diminishing returns. Dewees (1995) argued that households do not necessarily respond to declining fuelwood availability (resulting from increasing population pressure) by planting more trees. He reveals that various studies found that households respond to fuelwood scarcity by increasing labour time for fuelwood collection, using a lower quality of fuelwood, increasing reliance on dung and agricultural residues and purchasing fuelwood, which could have adverse environmental and economic impacts.

The foregoing discussion shows that while population growth may induce agricultural intensification, such process may be delayed or fail to take place due to lack of suitable technology, as well as economic, institutional and policy conditions that influence farmers' willingness and ability to adopt those technologies. On the other hand, high population density does not necessarily lead to environmental degradation and declining incomes.

2.5 Understanding farmers' decisions for agricultural intensification

Despite the availability of technologies with demonstrated technical efficiency that have beneficial effects on yields and the natural resource base, and despite all the efforts by governments of developing countries and donor organizations to promote their adoption, the adoption of these technologies by farmers remains very low in many African countries. Scientists from various disciplines have been investigating the process by which agricultural technologies are adopted by farmers for decades (Feder et al., 1985; Swanson *et al.,* 1986; Smit and Smithers, 1992; Rogers, 1995). These studies are broadly classified as sociological models that emphasize factors such as awareness and perception and economic models that emphasize access to markets, risks involved and liquidity constraints, which affect farmers' willingness and ability to invest on new technologies.

The sociological models consider adoption as a psychological process in which the potential adopter is assumed to move through several stages: awareness, interest, evaluation, trial and adoption. The characteristics of the new technology as well as personal and social factors are considered to be among the most important factors in the adoption process. These models emphasize education, extension and demonstration programs. Effective communication methods for disseminating information are emphasized as crucial components in promoting adoption (Hansen, 1987; Napier, 1991).

The economic models of technology transfer emphasize the impact of economic variables on the adoption of new technologies. These models are based on the premise that farmers do not adopt new technologies either because they do not have the necessary economic resources or because the practices are not profitable. Profitability of the technology, risks associated with its adoption, land tenure arrangements, and availability of credit are considered among the major factors that influence farmers' decisions.

In the remaining sections of this chapter we will discuss the theoretical and empirical links between poverty and land tenure on the one hand, and investment on NRM technologies on the other.

2.5.1 Poverty and land degradation

Poverty is cited as a major factor behind land degradation in many developing countries. This is because the rural poor in many developing countries depend heavily on their natural resources and lack access to alternative sources of income. Moreover poor households are usually marginalized to less fertile and steeper slopes, which are prone to high risks of soil erosion and could not be cultivated sustainably without the use of appropriate conservation measures. However, these farmers do not have the resources to undertake investments that enhance long-term productivity of their land (Blaikie and Brookfield, 1987; Mink, 1993; Cleaver and Schreiber, 1994; Barbier and Bishop, 1995). Poor households are also thought to have short time horizon due to lack of ability to forgo present consumption to maintain the quality of their natural resource base and ensure future consumption (Grepperud, 1996; Holden *et al.,* 1996; Prakash 1997).

Poverty is also believed to affect NRM indirectly through its effects on levels of education, population growth, and off-farm employment (Dasgupta, 1992). Poor households, for example, usually have higher family sizes because they live at a subsistence level and may consider children as an investment for their old age. They also have little or no access to education and, therefore, no access to information about birth control methods. Poverty, therefore, accelerates population growth among the rural poor and thereby the pressure on land.

The links between poverty, agricultural intensification and the environment are, however very complex and are conditioned by many factors (Ekobom and Bojo, 1999; Lee *et al.,* 2000). Reardon and Vosti (1995) maintain that the links between poverty and land degradation were not systematically explored. They introduce the concept of "investment poverty" and show that the links between poverty and land degradation are determined by the type of assets held by the rural poor and the type of environmental degradation they face. According to this theory, for example, "welfare-poor" household may not be necessarily "investment-poor", if they own abundant labour to build stone bunds from locally available materials but will still be "investment-poor" if the materials needed for stone bunds must be transported from afar and if this involves cash expenditures. Thus whether poor people in a given locality will adopt a given NRM technology depends on the type of poverty they suffer (lack of labour, capital etc.) as well as the type of technology in question.

Empirical evidences indicate that poor farmers respond in different ways to increased pressure on natural resources from population growth or market access. While some studies find that poorer households cope with the situation by expanding their cultivated land to more fragile areas, harvesting more trees etc. (Grepperud, 1996), which have adverse impact on the environment, others found that farmers adopt technical and institutional innovations, which protect or improve the natural resource base (Forsyth *et al.,* 1998 cited in Scherr 2000)[3].

2.5.2 Land tenure and land degradation

The way property rights are defined and enforced is a fundamental issue in the way land and other resources are utilized. Absence of secure right to their land is considered an important hindrance to investment on land and hence a cause of land degradation. Overexploitation of resources occurs because while the benefits from using resources under communal ownership accrue to individual users, the cost is shared by the community in general. This is termed as the "Tragedy of Commons" by Hardin (1968). Proper definition and enforcement of property rights is believed to facilitate efficient use of natural resources by internalizing the externalities associated with the use of the resource (Demestz,

[3] See Ekobom and Bojo (1999) for various hypotheses on how poverty and environments are linked and for some empirical evidence.

1967). Traditionally, nationalization and privatization have been two main solutions suggested to address the problem. Extremely high information and monitoring costs have discounted the success of nationalization and state management of resources (Edmonds, 2000).

Many economists maintained that privatization of common resources could be the solution to the overexploitation of resources (Coase 1960; Demestz 1967). The absence of clearly defined and enforceable property rights and associated externalities result in a sub-optimal investment in the management of the resources. Randal (1987: 154) summarized the characteristics of an adequate set of property rights as: "exclusive ownership including the right to use and to determine who, if any and under what condition can use the property; complete specification of the rights of owners and non owners and penalties for violation; transferability of rights including leasing and selling of rights to the highest bidder; and complete enforcement of property rights as rights which are not enforceable are not effective."

Private ownership of land is often considered to be superior to other land tenure systems in terms of its effect on the management of natural resources. The argument is that the security of tenure associated with private ownership of land encourages farmers to undertake long-term investments such as soil conservation structures and planting of trees (World Bank, 1992). Pearce and Warford (1993), however, have argued that private ownership of land may not be necessarily superior to communal ownership with respect to conservation of natural resources in developing countries for three reasons. First, the absence of documented land rights in developing countries does not necessarily mean that land rights do not exist. Many developing countries have historically evolved land rights that provide the security private ownership provides. Second, secure property right is a necessary but not sufficient condition for conservation of natural resources. In developing countries, where poverty is dominant and farmers have no access to credit, private ownership may be associated with unsustainable land use practices. Finally, title to land is largely meaningless unless it is effectively enforced. Due to the long-established traditional land ownership systems and the limited financial and administrative capacity of the governments in the developing countries, it is difficult to implement and enforce the land titling programs. Moreover, concerns about distribution of income and the extremely high costs associated with defining, enclosing and enforcing private patches of grazing and croplands proved to be the major constraints to the introduction of individual rights on communally owned lands in many developing countries (Bojo, 1991).

Recently communal management of common property resources has risen as a popular alternative system of property rights (Ostrom, 1990). The Earth Summit (United Nations Conference on Environment and Development, 1992) has emphasized that community management of resources is vital for sustainable development (Leach *et al.,* 1999). It is argued that communities with communal property relations usually develop a system of resource management that exhibit their concern and sense of responsibility. Pearce and Warford (1993), for example, observed that rural people in developing countries have impressive knowledge of their environment and are able to establish elaborate rules and regulations that enhance sustainable use of their resources. They, however, maintained that the communal management systems broke down as population pressure on natural resources increased with population growth and technological change.

Empirical evidences on the effect of land tenure on NRM show mixed results. Using field data from 8 villages in Burkina Faso, Kazianga and Masters (2002) studied the determinants of investment in field bunds and micro catchments and computed the elasticity of adoption and intensity of use of these technologies. They found that farmers who have more ownership rights over a farmland tend to invest more on soil conservation and concluded that clearer property rights over croplands and pasture could help to improve the management of those resources.

Gebremedhin and Swinton (2000) examined the management of private and communal lands in Tigray, a northern province of Ethiopia. Using data from 250 farm households, they found investments in stone terraces to be highly sensitive to discount rates, the pay back period varying from 5 to 14 years. This was much longer than the period farmers expect to cultivate their land in the area. They also found that land tenure security (which was measured by the expectation of bequeathing the land to children and the length of period from the last land redistribution) was the most important determinant of adoption of soil conservation technology on private land.

Edmonds (2000) examined the impact of government-initiated community institutions on local resource management in Nepal in which the government transferred accessible forests over to local communities. By comparing household's fuelwood extraction between areas that have received forest groups to areas that have not, they found that government-initiated community institutions to manage local resources were associated with a significant reduction in resource extraction.

Kundhlande and Luckert (1998) argued that there may be key differences between tenure types all termed communal and a meaningful analysis of the impact of tenure on investment incentives requires a closer look into the wide range of arrangements in each type of tenure. Thus they developed taxonomy for describing property rights to natural resources and applied it to the Zimbabwean case study from which they concluded that promotion of tree planting may work on some tenure types but fails on others. Warner (1995), in a study of the patterns of tree growing in East Africa, observed that the idea that farmers will not make long-term investment in their holdings unless there is a degree of security associated with private property was not borne in the region where most land is held under customary law and ultimately owned by the state. She notes that most farmers in the area feel secure about their holdings and this is exhibited in the large number of trees they planted. She acknowledged that the number of trees increased with the introduction of new individual tenure rights in Kenya. However, she argued that the main reasons for the increased tree planting were the need to establish a boundary for their land and reduced access to off-farm resources as nearby areas were privatized and not improvement in security of tenure.

Chapter 3

Agriculture, Energy and Land Degradation in Eritrea

3.1 Introduction

Agriculture, energy and land degradation are closely related in rural areas of Eritrea. The agricultural sector is currently the major link between the economy and the environment. The major types of land degradation in the country, soil erosion, nutrient depletion and deforestation are mainly due to traditional low external input farming practices, expansion of agriculture into marginal areas, overgrazing and high dependence on biomass energy. This chapter discusses the major characteristics of the agricultural, forestry and energy sectors, the nature and extent of land degradation and the underlying causes of land degradation in the Highlands of Eritrea.

3.2 The state of Eritrean agriculture

At present agriculture is the most important sector in Eritrea. With over 70 percent of its population employed in agriculture the country may be described as agrarian. Crop and livestock sectors together provide a means of livelihood and the basis for food security for the majority of the population. The contribution of the sector to the national economy, however, is very modest both due to the small scale of the farms and low productivity. Agriculture contributes about 16 percent to the gross domestic product. The country's domestic grain balance is generally less than the consumption requirements, and often much less.

3.2.1 Land size and land use

In terms of land size Eritrea may be considered well endowed relative to its population. The total population of Eritrea is estimated at 4 million in 2000. This means that the average population density for the country in that year[4] was about

[4] Given the current high levels of population growth in the country, population will double every 25 years.

32 persons per km^2. These figures could, however, give a misleading view of the pressure on land resources, as they do not distinguish between the highlands and the lowlands, which are characterized by varying degrees of population concentration and economic activities. The Highlands of Eritrea comprise about 16 percent of the total land area and are settled by more than half of the total rural population of the country. The lowland areas, which comprise the largest proportion of the country's land area, are occupied by pastoral and agro-pastoral societies. Sedentary farmers mostly live in the highlands with crop production as the main economic activity. In most parts of the Highlands of Eritrea shortage of land is a serious problem. In fact it has been a root cause of social conflicts and environmental degradation.

Moreover, due to rugged topography in the highlands and climatic conditions unsuitable for agriculture in the lowlands, only 12 percent of the land is suitable for rain-fed agriculture (FAO, 1994; MOA, 2002b). Only 3.5 percent of the total land or 29 percent of the potentially cultivable land is currently under cultivation (see Table 3.1). While there remain vast areas in the western lowlands suitable for rain-fed cultivation, which are not currently cultivated, almost all the potentially cultivable lands in most parts of the Central Highlands are already cultivated. In fact, crop production in many areas of the highlands has been extended to steep-slope hillsides leading to high levels of soil erosion. Table 3.1 shows that more than 50 percent of the land is used for grazing and more than one third of the land is either too dry or too degraded to be used for any economic activity.

Table 3.1 Land use in Eritrea, 2001

Land use	Area (1,000 ha)	Percent
Cropland	439	3.5
Rain-fed	417	
Irrigated	22	
Grazing land	7,000	56.3
Woody Vegetation	737	5.9
Highland forest	53	
Plantations	10	
Woodland	674	
Urban land	13	0.1
Barren land	4,243	34.1
Total	12,432	100.0

Source: MOA (2002b)

3.2.2 Crop production

Crop production in Eritrea is mainly cereal-based with barley, wheat and taff grown in the highlands and sorghum and millet grown at lower altitudes. Pulses, mainly chick peas, beans and peas are grown in the highlands while oilseeds are more important in the lowlands. The total area cultivated to each crop and crop yield in the period 1994-2004 is given in Table 3.2.

Despite the high proportion of population employed in the agricultural sector, domestic production of food crops is much lower than the country's food requirements. Domestic cereal production in the past 10 years on average met only 40 percent of the total cereal requirement of the population, but in some years it was as low as 10 percent (FAO, 2005). Riely (1995) observed that crop production in 1994, which at the time was described as the best in recorded history, covered only 44-59 percent of the food requirement of the population that he predicted that Eritrea would continue to face a food deficit in the foreseeable future. Cultivated area and yield of the major crops in 1998 were 22% and 41.5% higher than that of 1994. Nevertheless, total production was still much lower than domestic food requirements. Even in good years, the country produces only 60 percent of its food needs. This is a result of the combined effects of small cultivated area and low yield levels.

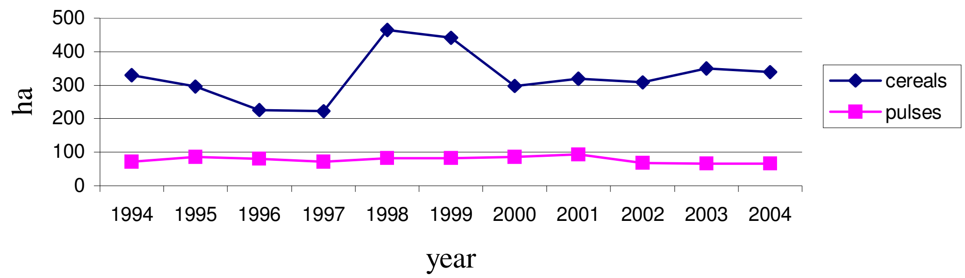
Average farm size is generally less than 1 hectare per household in the Central Highlands and 2 hectares in the lowlands. The average per capita cropland is 0.14 hectares or 0.7 ha per household (assuming a family size of 5 persons). This is almost half the size of per capita croplands in SSA (MOA, 2002b). Moreover, both cultivated land and crop yields vary considerably from one year to the other. Figure 3.1 shows the total area of land cultivated with cereals and pulses in the last 10 years. As will be shown in the next section, rainfall is highly variable in its magnitude and distribution in the country. This is one of the main causes of the variation in crop production because it affects both the size of cultivated land and crop yield. The decline in cultivated area in 1999 and 2000 after reaching their peak in 1998 is clearly due to the border war with the neighbouring Ethiopia, which led to the displacement of many rural households in Debub and Gash Barka regions (Figure 1.1). In addition, the mobilization of a large proportion of the population in the army has contributed to the drastic decline in cultivated land in those years. Due to consecutive droughts and the still unresolved border conflict cultivated area remained at low levels.

Table 3.2 Cultivated area (1,000 ha.) and yields (100 kg/ha.) 1994 – 2003

	1994		1995		1996		1997		1998		1999		2000		2001		2002		2003	
	Area	Yield	Area	Yield	Area	Yield	Area	Yield	Area	Yield	Area	Yield	Area	Yield	Area	Yield	Area	Yield	Area	Yield
Cereals	**330.45**	**7.82**	**296.22**	**4.15**	**225.00**	**3.70**	**223.00**	**4.25**	**464.02**	**9.87**	**440.52**	**7.24**	**296.97**	**4.06**	**318.61**	**6.53**	**307.70**	**2.05**	**349.71**	**2.99**
Sorghum	131.00	9.20	130.07	4.70	100.00	3.92	120.00	4.64	236.23	11.42	236.37	8.77	146.39	4.23	165.82	4.75	166.30	2.02	200.93	3.19
Millet	87.06	6.77	60.24	2.12	50.00	2.48	30.00	2.50	83.00	6.24	80.00	2.90	40.73	1.11	40.42	7.49	40.00	1.45	40.00	4.23
Barley	38.86	7.57	43.32	6.45	25.00	5.13	28.00	5.75	45.55	12.42	43.38	7.34	46.35	5.58	48.38	9.29	40.01	2.43	43.96	1.91
Wheat	18.15	8.26	16.44	6.06	14.00	5.61	10.00	5.13	33.43	5.50	35.70	7.70	23.18	5.94	22.46	11.32	26.16	4.97	20.00	2.38
Maize	24.10	8.24	15.99	3.37	11.00	4.29	15.00	4.28	38.49	7.53	20.07	7.92	20.32	2.00	11.53	7.85	5.23	5.76	13.36	3.34
Others	31.28	4.75	30.16	1.91	25.00	2.53	20.00	2.08	27.32	6.85	25.00	5.26	20.00	5.20	30.00	6.50	30.00	1.06	31.46	2.27
Pulses	**71.71**	**6.03**	**85.80**	**6.58**	**81.20**	**6.26**	**71.30**	**6.41**	**82.87**	**6.60**	**82.69**	**6.16**	**85.65**	**5.58**	**94.07**	**5.87**	**68.03**	**5.78**	**66.30**	**5.61**
Beans	4.96	7.24	6.50	7.69	6.50	7.69	2.00	2.50	2.00	3.48	4.34	7.58	2.85	4.97	4.41	9.12	1.70	2.62	2.00	3.00
Broad beans	4.90	4.12	5.50	5.46	7.00	5.71	4.00	5.00	5.00	6.00	4.00	5.00	4.00	4.50	4.00	4.50	4.00	4.50	4.00	4.50
Peas	1.90	5.02	7.00	4.93	6.50	5.09	2.50	4.84	5.00	4.36	4.50	4.00	4.50	3.64	3.00	3.78	3.80	7.36	3.80	7.36
Chick peas	1.15	9.91	1.30	7.69	1.70	8.82	1.30	7.69	3.37	5.30	6.84	4.08	11.80	2.51	20.16	4.09	4.03	4.39	4.00	4.25
Lentils	2.80	8.93	3.50	8.57	4.50	8.89	3.50	8.57	5.50	9.09	5.00	8.00	4.50	6.67	4.50	6.67	4.50	6.67	4.50	6.67
Vetch	8.00	5.00	10.00	5.00	12.00	5.00	9.00	4.44	11.00	5.46	10.00	5.00	10.00	5.00	10.00	5.00	10.00	4.50	10.00	4.50
Others	48.00	6.04	52.00	6.92	43.00	6.27	49.00	6.94	51.00	7.06	48.00	6.67	48.00	6.67	48.00	6.67	40.00	6.25	40.00	6.25
Oilseeds	**61.70**	**1.37**	**63.30**	**1.69**	**56.90**	**1.26**	**52.50**	**1.19**	**53.45**	**1.41**	**50.69**	**1.46**	**49.59**	**1.35**	**46.25**	**1.29**	**42.70**	**1.30**	**44.84**	**1.76**
Total Area*	**502.30**		**485.40**		**400.4**		**388.4**		**647.90**		**563.40**		**502.00**		**458.93**		**418.43**		**460.85**	

* Total cultivated area includes land cultivated with vegetables and perennials and therefore is greater than the sum of the components.
Source: FAOSTAT

Figure 3.1 Total area cultivated under cereals and pulses in Eritrea: 1994-2004



Source: Based on FAOSTAT

Agricultural productivity is very low because of low and erratic rainfall, poor and shallow soils and little use of modern agricultural practices. Agricultural practices in the Highlands of Eritrea are largely traditional and rain-fed. The same resources and the same type of farming technologies have been used for centuries. The traditional oxen-drawn, simple iron-tipped plough and wooden tools are the major type of farm implements in the region. Improved crop varieties and pesticides are rarely used in the country. It is estimated that only about 10 percent of the farmers use inorganic fertilizers at low rates. The average rate of fertilizer application in 2002 was 22 kg/ha. This is much lower than the recommended rate of 150 kg/ha (FAO, 1994; EarthTrends, 2003). Due to deforestation and the resulting shortage of fuelwood, manure is rarely applied on crops and is primarily used as a source of household fuel. The 30 years war for independence and the recent border war as well as recurrent droughts have also devastated the economic base of the rural people. Table 3.3 shows some parameters that indicate the state of Eritrean agriculture in comparison to the agricultural sector in SSA and the world.

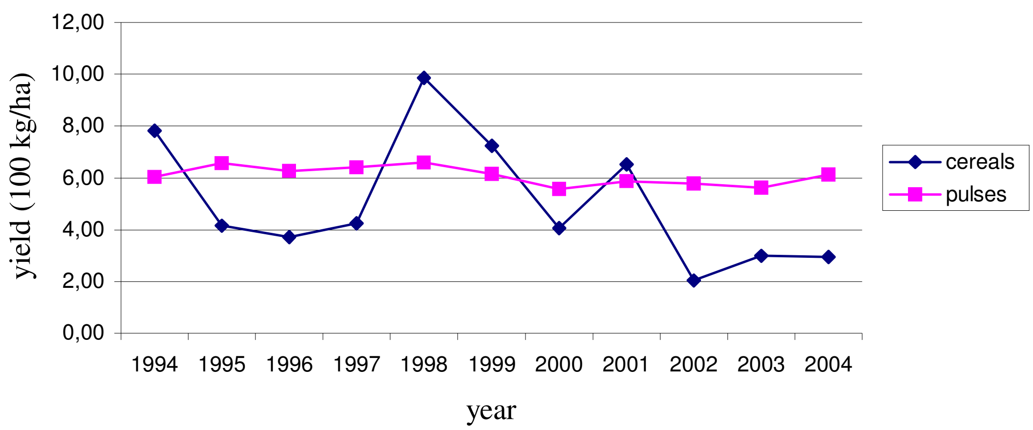
Table 3.3 Indicators of agricultural performance

	Eritrea	Sub-Saharan Africa	World
Cereal production (kg/person), average of 1999-2001	62.0	135.0	343.0
Average yield: cereals (kg/ha)	671.0	1,221.0	3,096.0
Average yield: pulses (kg/ha)	529.0	481.0	808.0
Hectares of land per 1000 population, 1999	142.0	274.0	251.0
Percent of cropland that is irrigated, 1999	4.4	3.8	18.3
Intensity of fertilizer use, (kg/ha) 1999	22.0	12.0	94.0
Number of tractors per 1000 ha Of croplands, 1997	0.9	1.5	17.5

Source: EarthTrends (2003).

Figure 3.2 shows yields of cereals and pulses between 1994 and 2004. As stated earlier crop yields in Eritrea are not only low but are also highly variable. While shortage of rainfall, low levels of input use, and traditional farming practices are the major causes of low levels of crop yields, the high variability in crop yield is mainly a result of fluctuations in rainfall.

Figure 3.2 Yields of cereals and pulses in Eritrea, 1994-2004



Source: Based on FAOSTAT

The Government of Eritrea has introduced a semi-commercial rain-fed agriculture, which it called Integrated Farming Scheme (IFS), in 1997. The objective of the IFS is to replace the low-productivity traditional methods of cultivation by integrating the inputs required to increase crop yield into a package and mechanizing crop production. As the small farm size (less than 1 ha. per family) is not technically and administratively conducive to facilitate IFS, farmers participating in this scheme pool their land resources into large fields and contribute labour. This scheme, which requires farmers to organize themselves into what appeared to be a collective farming system, provides participating farmers chemical fertilizer, seed and tractor services on credit. The total land cultivated under the IFS was 55,000 and 115,000 hectares in 1998 and 1999 respectively. The IFS were concentrated in southern Gash-Barka region, which has the highest potential for rain-fed crop production in the country. While crop yields in the IFS more than doubled, the sustainability of the program was questioned due to low loan repayment rates (Tikabo, 2003).

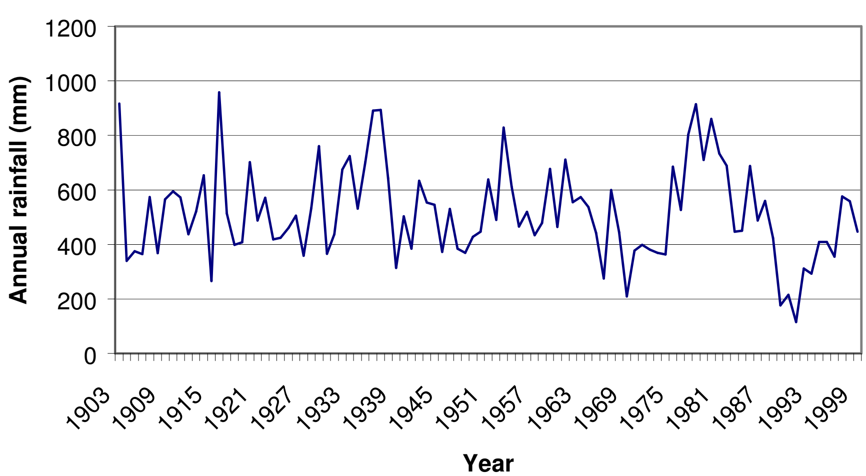
Climate and rain-fed crop production

Based on agro-climatic and soil parameters, Eritrea is classified into six agro-ecological zones: the Central and Northern Highlands Zone; the Western

Escarpment Zone; the South Western Lowland Zone; the Green Belt Zone; the Costal Plains Zone and the North Western Lowland zone. Due to its location and the physical features of its land, the country generally experiences scarce, erratic and unevenly distributed rainfall. Annual rainfall decreases from south to north, from more than 700 mm in some parts of the southern border with Ethiopia to less than 200 mm at the northern border with the Sudan. Rainfall also varies in amount and season between the different regions of Eritrea. The Country has two main rainy seasons: summer and winter rains. Most of the country receives the summer rainfall with the main rainfall period starting in June and reaching its peak in July and August. The Coastal Plains experience the winter rainfall from November to March. The eastern escarpment located in the Green Belt Zone enjoys both the winter and summer rains because of its location.

The scarcity of rainfall in most parts of Eritrea is evident with one third of the country receiving less than 200 mm average annual rainfall and 90 percent receiving less than 600 mm (FAO, 1994). Of the six administrative regions of the country, only two (Debub and Maekel) are classified as dry sub-humid. The rest are classified as semi-arid or arid (MOA, 2002a). Limited and unreliable rainfall is the major constraint to increased crop production in most parts of Eritrea. A study by Cliffe (1992) showed that lack of rainfall was the most important factor limiting crop production in the years 1986 to 1987. An MOA report also showed that crop harvest in 1993 was only 20 percent of the expected crop harvest, inadequate rainfall being the major underlying reason for such a disastrous crop failure. Figure 3.3 shows that there is a high fluctuation in annual rainfall in Eritrea. A statistical analysis of the annual rainfall between 1913 and 2000 has shown that rainfall has not significantly decreased during the last century (Mebrahtu *et al.,* 2004). However, it has been reported that rainfall has shown a decreasing trend over the last decade (FAO, 2005).

Figure 3.3 Annual rainfall in Asmara (Central Highlands Zone)



Irrigation

In addition to the traditional subsistence farming practices that dominate the highlands of Eritrea, small-scale irrigation is practised in some areas of the country. Irrigated agriculture was introduced to Eritrea by the Italians at the end of the nineteenth century. Most irrigation practices make use of diversion of streams (known as spate[5] irrigation) but some depend on boreholes, wells, pond water and dams. The area under horticultural crops in Eritrea in 2004 has been estimated at about 6407 hectares. This mainly includes small pumped irrigation schemes in Debub, Maekel and Anseba regions, where potatoes, tomatoes, carrots and other vegetables and fruits are grown. More than 20,000 hectares are also estimated to be under spate irrigation where, most frequently, sorghum is sown on the escarpments (FAO, 2005). Considerable attention is given by the government and non-government organizations (NGOs) to irrigation in the country. Permanent diversion structures have been constructed and a number of wells and dams have been dug or constructed before and independence for supplying water both for irrigation and drinking. However, only few of the dams are used for irrigation due to various reasons. They include absence of irrigable land below the dams; insufficient capacity to allow use by all members of the villages and absence of institutional capacity to manage water resource; and lack of irrigation experience among the peasants and absence of effective extension on the part of MOA. Moreover, most of the dams were built without irrigation outlet and well-planned irrigation layout for canals (Kiflemariam, 2001).

3.2.3 Livestock

Livestock production is an important component of the farming system in Eritrea. There are two main livestock production systems practised in the country. The agro-pastoral production system, which combines crop farming and livestock rearing, is mainly practised in the highlands and involves raising livestock mainly cattle, sheep, goats, camels and equines for milk, meat, animal power, and for sale. In the pastoral production systems, on the other hand, livestock are mainly kept for the supply of milk, meat and for sale. This is mainly practised in the lowlands with cattle, sheep, goats and camels the main types of livestock.

The livestock population in the different regions of the country in 1997 is presented in Table 3.4. Given that 70 percent of the population live in the rural areas and assuming a an average family size of 4.5 persons per household, the

[5] Spate irrigation is a system of irrigation that makes use of seasonal rivers producing floods of short duration from the highlands. These floods are diverted by structures to irrigate land in the lowlands.

average number of livestock per household is 3.1 cattle, 3.4 sheep, 7.5 goats, 0.5 camels, 0.8 donkeys and 1.8 chickens.

Table 3.4 Livestock population by region, 1997

Region	Cattle	Sheep	Goats	Camels	Equines*	Chickens
Anseba	218,923	124,300	620,023	25,266	61,603	78,247
Debub	490,093	614,069	706,409	19,382	173,703	512,776
Gash Barka	917,344	675,268	1,745,784	113,263	176,139	423,898
Maekel	40,505	149,927	23,556	0	24,676	86,425
Northern Red Sea	178,532	462,333	994,596	107,032	61,140	26,867
Southern Red Sea	82,060	103,047	571,417	53,971	21,198	6,052
Total	1,927,457	2,128,944	4,661,785	318,914	518,459	1,134,265

* Mostly donkeys but include some horses and mules.
Source: MOA (1997)

Livestock productivity is low due to lack of adequate nutrition, poor quality herds and lack of access to veterinary facilities. Since little forage crops are planted in Eritrea, livestock entirely depend on common grazing lands and crop residues. The rangelands in the highlands of the country are generally steep and infertile. Due to the communal land ownership and high population pressure in the highlands of the country, overstocking is a common phenomenon. Deforestation, continuous grazing and the loss of fertile topsoil has substantially reduced the potential productivity of grazing lands. Seasonal migration of livestock (sometimes even across the boarder to Ethiopia and Sudan) in search of feed and water is a common strategy of coping up with shortage of feed both in the highlands and lowlands. In years of extreme droughts, farmers sell their livestock both due to lack of feed and to make up for shortfalls in food production. This often has a negative long-term effect, as livestock, particularly oxen, are key factors in crop production.

3.3 Energy and forestry in Eritrea

Energy and forestry sectors in Eritrea, as in many developing countries, are highly related. This is because of the high dependence of the majority of the population on biomass for their daily energy uses. This over-reliance on biomass as a source of energy is one of the major factors behind the high level of land degradation in the country. An increased tree cover can positively contribute to the problem of land degradation in two ways. First, increased tree cover improves the quality of land directly by decreasing soil erosion and increasing fertility. Second, increased tree cover means rural households will have better access to fuelwood. This will allow dung and crop residues to be used for fertilizer with a positive impact on soil structure and nutrient balance. This section looks at the structure of energy consumption and the state of forestry in Eritrea.

3.3.1 Energy

Eritrea has one of the world's lowest energy consumption rates. Per capita energy consumption is about 8.12 Giga Joules per year. Commercial energy products (electricity plus oil products) constituting only one third of the total energy consumption (MOEM, 2000). A comprehensive energy database was established by Eritrean Ministry of Energy and Mines (MOEM) in 1995 and was updated in 1998. Table 3.5 shows that about 97 percent of all biomass fuels in 1998 were utilized by the household sector for cooking and heating purposes. Liquefied petroleum gas (LPG) and kerosene are also mainly used in the household sector, about 80 percent of the former and 89 percent of the later being consumed by that sector. While LPG is exclusively utilized in the urban centres (mostly the capital city) for cooking purposes, kerosene is used both in the urban and rural areas of the country.

The transport sector utilizes more than 87 percent of gasoline and about 44 percent of diesel consumed in the country. No electricity is utilized in the transport sector. More than 54 percent of gasoline is consumed in the public /commercial sectors which also use 20 percent of the electricity consumption in the country. The Industrial and household sectors are the major consumers of electricity in Eritrea constituting about 49 percent and 35 percent respectively.

About 80 percent of the Eritrean population has no access to electricity. Electricity is available only in the larger cities and towns and a few villages near them. Few other villages have community diesel generators, which can provide electricity of 30 to 100 Watts in the early hours of the evening. Except in the major cities of the country, electricity in household sector is exclusively used for lighting purpose because most households are too poor to afford the necessary electrical appliances and to pay higher bills.

Different activities are underway by the Ministry of Energy and Mines to diversify sources, increase efficiency and expand access to electricity in the country. To diversify energy sources wind, solar and alternative uses of biomass energy are being actively investigated. Large-scale tree planting activities are being undertaken by mobilizing community labour and students summer programs, which are expected to increase the supply of fuelwood. Major investments are also being made to change the national electricity supply system and to install higher voltage lines to enhance efficiency. The Ministry is also undertaking a research to arrive at affordable and more efficient cooking stoves to reduce the amount of fuelwood required for cooking. Some studies indicate that improved stoves that use iron plates instead of the traditional clay plates (*Mogogo*) can double the efficiency of the use of fuelwood (Van Buskirk *et al.,* 1998).

In conclusion, biomass fuels and particularly fuelwood is presently the most important source of household energy and the only source of energy for almost all rural households in Eritrea. While the government of Eritrea is making tremendous efforts to increase the supply of energy and improve the efficiency with which fuels are utilized, owing to the distribution of the rural population and the financial constraints of the country, the rural population is likely to continue to heavily depend on biomass energy.

Table 3.5 Energy demand by fuel type and sector in 1998

	Biomass (1,000 tonnes)				Oil Products (1,000 tonnes)				Electricity (GWh)
	Fuel Wood	Dung	Agr. Residue	Charcoal	LPG	Kerosene	Gasoline	Diesel	
Household	800.50	261.47	87.27	70.69	0.65	18.89	0	0	57.06
Public/Comm	30.18	3.90	3.52	2.61	0.17	2.27	2.15	46.62	31.18
Industry	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.92	63.97
Transport	0.00	0.00	0.00	0.00	0.00	0.00	13.88	56.00	0.00
Total	830.68	265.37	90.79	73.3	0.82	21.19	16.03	103.54	152.21

Source: MOEM (2000)

3.3.2 Forests and woodlands

Forest resources in Eritrea are few and highly degraded due to high human and livestock pressure on them from collection of wood for fuel and construction materials, grazing and expansion of agricultural land. Nevertheless, forests and woodlands still contribute considerably to the Eritrean economy and particularly to the rural population. Rural communities, most urban households and some commercial enterprises depend on fuelwood for energy. Forest products also serve for construction materials and as a source of feed for livestock. In addition to the above uses, other non-wood forest products in Eritrea include Gum Arabic, Gum Olibanum and dried Doum Palm leaves (FAO, 1997).

The land use categories in Eritrea were described in Table 3.1. In this section we present the nature of the forests and their distribution in the country in more detail.

Table 3.6 Natural forest vegetation areas of Eritrea by region (km^2)

	Administrative regions						
	Anseba	Maekel	D.K. Bahri	Debub	S.K. Bahri	Gash-Barka	Total
Forest							
Closed to medium closed[6]	14	77	0	37	463	0	591
Open	133	0	0	15	262	0	410
Woodland							
Closed to medium closed	523	8	0	448	832	2722	4533
Open	901	18	1235	1471	1555	4360	9541
Bush							
Grassland/wooded grassland	13,943	52	3,678	907	669	6,327	25,577
Bushland	3,950	282	9,556	1,095	29,416	9,526	53,824
Other Forest							
Riverine forest	341	0	43	99	110	1,272	1,865
Mangroves	0	0	45	0	19	0	64
Other Categories							
Barren soil	1,868	3	10,344	115	4,532	1,403	18,265
Agriculture	527	796	0	3,805	857	2,726	8,712
Other	4	39	116	0	9	67	234
Not classified	581	0	0	0	0	1,591	2,172
Total	22,784	1,274	25,018	7,992	38,724	29,995	125,788

Source: FAO (1997)

As shown in Table 3.6, the FAO (1997) study classifies the natural forest cover in Eritrea into six major vegetation types viz. Highlands Forests, Mixed Woodland, Bush or Shrub land, Grassland and Wooded Grassland, Riverine Forests and Mangrove. The Forests of the country mainly consist of closed and open coniferous and African Olive forests and cover about 1000 km^2 or 0.8 percent of the total land area of the country. In addition, the country has important vegetation composed of woodlands, riverine forests and mangroves of about 16000 km^2 (12.7%), which brings the total forest cover to 13.5 percent of the total surface of the country. The category Bush is the dominant vegetation type covering 63% of the total area. This category is generally open with shallow and rocky soils.

Geographically most of the forests are found in the highlands of the country and the eastern escarpments. More than 72 percent of the open and closed forests of the country are found in Semienawi Keih Bahri and 14.7% are found in Anseba. Of the six regions in Eritrea, Debubawi Keih Bahri and Gash-Barka has none of these forests. On the other hand, 50 percent of the woodlands are found in Gash-Barka. The Mangroves are found in the two coastal regions – Semienawi Keih

[6] Closed and Open (forests or woodlands) refer to vegetation cover of greater than 40% and 10%-40% respectively.

Bahri and Debubawi Keih Bahri. The largest part of the Riverine forests (83.6%) is found in the western lowlands. Gash-Barka and Anseba constitute 65.9 and 17.7 respectively of the riverine forests. A number of activities directed at managing natural forests and woodlands as well as establishing new plantations are underway in Eritrea.

Management of Natural Forests

The government of Eritrea has initiated a closure program in which existing forests and woodlands are brought under full or partial protection by restricting human activity (such as fuel collection, farming and grazing) so that existing forests may be protected and degraded woodlands may get the chance for regeneration. The two types of closures found in the country include 'permanent closure' where the area is restricted from human activity for unlimited period of time and 'temporary closure' where the restriction is carried out for a limited period, from a few months to a few years (FAO, 1997). Generally the permanent closures have relatively more forest cover including tree species with valuable timber quality than the temporary closures. The size and distribution of the closures in the different regions of the country are presented in table 3.7.

Table 3.7 Permanent and temporary closures in Eritrea

	Permanent Closure		Temporary Closure	
Zoba	No.	Area (ha)	No.	Area (ha)
Anseba	17	8,138	2	64
Debub	24	13,843	16	8,650
Debubawi K. Bahri	0	0	0	0
Gash-Barka	10	23,435	10	1,290
Maekel	7	4,990	5	4,500
Semienawi K.Bahri	20	59,932	0	0
Total	**78**	**110,338**	**33**	**14,504**

Source: FAO (1997).

As indicated in table 3.7, there are currently about 125,000 hectares of protected forest and woodland areas in Eritrea of which 110,338 in permanent closure and the rest in temporary closure. Fifty four percent of the total area under permanent closure is found in Semienawi Keih-Bahri region. The next two regions that have the largest area of permanent closures are Gash-Barka and Debub with 21% and 12.5% of the area under permanent closure respectively.

Most of the temporary closures (91%) are located in the Highlands of Eritrea in Debub and Maekel regions. This is because the temporary closure system has been traditionally practised in the highlands for management of grazing lands. Thus, in addition to the closures recorded by the survey, there may be many more temporary closures in the country.

Plantation resources

Afforestation programs have been undertaken in Eritrea for the last two decades. As a result, in addition to the natural forests, some plantations exist in the country. Most of the plantations have been established by the government as part of the hillside catchment planting campaigns with the primary objective of soil and water conservation. The size and distribution of the plantations that existed in 1997 are presented in Table 3.8.

Table 3.8 Summary of plantations

Zoba (region)	No. of Plantations	Gross Area (ha)
Anseba	39	3,986
Debub	44	1,403
Gash-Barka	8	704
Maekel	29	3,344
S.K. Bahri	11	5,305
National	131	14,741

Source FAO (1997)

While the records of the Ministry of Agriculture indicate that over 50,000 hectares of land have been planted, the FAO field survey shows that less than 15,000 hectares of plantations existed in 1997. The discrepancy between the records of the Ministry and the FAO estimates is due to the fact that the records of the Ministry indicate areas planted each year which often includes replanting of previously planted areas to improve the stocking rate. Since soil conservation and not production of wood was the primary objective of the tree planting programs, most plantations were established on inherently low potential hillsides with shallow soils. This, together with defective seedlings and inadequate rainfall, contributed to modest survival rates (60%) and the need for replanting.

As most plantations were undertaken by the government under the FFW (this has been changed to Cash for Work (CFW) in recent years) programs, people participated in the establishment of the plantations. However, the programs did not have any mechanism to ensure community participation beyond that. The communities were not able to identify themselves with the objectives and outputs and therefore their participation continued only as long as they were paid for it. With the exception of a few plantations that have been handed over to the communities after independence, the communities were not allowed to harvest the output.

In addition to the plantations established by the government, there also exist some farm and homestead plantations in the country. Farmers in many parts of the country exhibit high interest in individual tree planting. This, however, is constrained by the lack of sufficient land around their house. Tree planting on farmlands are not common because the periodic redistribution of land is not conducive for planting perennial crops with long gestation period. In addition, farmlands are used for grazing after harvest. Thus either the community does not allow individual tree planting on croplands or the farmers are not interested because survival of the seedlings is unlikely due to livestock browsing. An innovative solution has been made to these problems in some villages of Zoba Maekel in which the communities have set aside a certain area for tree planting and each farmer who is interested in tree planting is assigned a plot in that area. The participation of the community in such plantations is high. The government can encourage other communities (villages) to undertake similar steps to deal with the tenure constraint in individual tree planting.

3.4 Land degradation

Nature and extent of land degradation

Land degradation is defined as "a loss of land productivity through various processes such as erosion, wind blowing, salinization, water logging, depletion of nutrients, deterioration of soil structure and pollution" (Dudal, 1981: 4). Land Degradation thus involves several processes and can be manifested in many different forms. These include water and wind erosion, biological degradation (loss in humus), physical degradation (increase in bulk density, decrease in permeability), chemical degradation (acidification, toxicity) and excess salts (salinization, alkalization) (Bojo and Cassels, 1995).

The Ethiopian Highlands Reclamation Study (EHRS) found that biological degradation was the most prevalent and most serious feature of all agricultural land in the highlands of Ethiopia.[7] Biological degradation sets in when the soil surface is deprived of the supply of plant residues and is therefore exposed to extremes of heat or wetness. This form of degradation is also the cause of physical degradation and accelerated erosion in the region. Soil erosion is viewed as one of the major environmental problems in the Highlands of Eritrea (FAO, 1994; GOE, 1995). Hawando (1994) underlines that land degradation in Eritrea has reached a very serious level that this has resulted in a dramatic decline in yield levels.

Most of the reports on the extent of land degradation in the country and the impacts on yield are, however, made based on scanty data. Estimates on soil

[7] The study included the highlands of Eritrea.

erosion are based on a single research station (Afdeyu Research Station (ARS) in Zoba Maekel)[8] and/or extrapolations from other countries. Based on these sources, FAO (1994) puts average annual soil erosion for the different and soil conditions in Eritrea between 2 and 25 tons per hectare and the average annual soil loss from croplands at 15 tons per hectare.

The above figures are gross soil losses and do not take into account redeposition of soil from one type of land use to another. By taking into account land use and rainfall conditions in Eritrea, Bojo (1996) has modified the rates of soil loss estimated for the Ethiopian Highlands (Hurni, 1988) and constructed a 'soil transfer matrix' for Eritrea (Table 3.9). The soil transfer matrix shows the transfer of soil between different categories of land use. For example, the gross loss from croplands is 21 tons per hectare per year. The annual rate of deposition from the different types of land use categories to cropland is 9.1 tons per hectare resulting in a net loss from croplands of 11.9 tons per hectare per year. While admitting that some of the assumptions used to derive the soil transfer matrix are questionable, Bojo (1996) emphasized that the major conclusion from the matrix is that the net rate of soil loss from croplands is considerably lower than the gross rate of loss.

Table 3.9 Soil erosion and deposition in Eritrea

	Total area (1,000 ha)	Percent share in total land	Estimated gross annual soil erosion (tons per ha)	Annual soil redeposition, by land use ((tons per ha)					Total eroded soil which is lost to the system (tons per ha)
				Grazing	Barren	Woodland	Cropland	Forest	
Grazing	6,967	57.2	2.5	2.0	0.3	0.3	0.3	0.3	0.3
Barren	4,047	33.2	35.0	7.6	16.3	7.6	7.6	7.6	3.5
Woodland	673	5.5	2.5	0.1	0.1	0.2	0.1	0.1	0.3
Cropland	439	3.6	21.0	0.7	0.7	0.7	1.1	0.7	2.1
Forest	63	0.5	1.0	0.005	0.005	0.005	0.005	0.007	0.1
Total	12,189	100.0		10.4	17.4	8.8	9.1	8.7	
Net loss (gain)				(7.9)	17.6	(6.3)	11.9	(7.7)	1.5

Source: Bojo (1996).

Effects of land degradation

The impact of soil loss on agricultural production is even more difficult to estimate with any degree of reliability. The relationship between soil erosion and crop yield is very complex because soil erosion reduces crop yield by, among other things, decreasing the water-holding capacity of the land, reducing the rooting zone and decreasing nutrients available for plants. In addition, the

[8] Results from ARS are discussed in more detail in Chapter seven.

relationship between soil loss and crop yield is non-linear. While soil loss may not have any effect on yield in deep soils, it may reduce yield in shallow soils considerably (Eaton, 1996).

Estimations of yield decline due to soil erosion in Eritrea are based on a similar study in Ethiopia. Hurni (1988) estimated crop yields in the Ethiopian Highlands were declining at a rate of 2 percent per year. Bojo and Cassels (1995) considered lower rates of soil loss (due to redeposition) and arrived at a much lower rate of yield decline. Modifying these calculations for Eritrean conditions, annual yield losses for Eritrea are estimated between 0.6 and 0.3 percent per year (World Bank, 1996a).

The depletion of nutrients for African countries is generally very high (Stoorvogel and Smaling, 1990). Evidence on the extent of nutrient loss and its impact on agricultural production, however, do not exist for Eritrea. The use of cow dung for household fuel is believed to have much more impact on agricultural production than soil loss. Estimations of the value of agricultural output foregone due to burning dung vary from 2.2 percent (MOA, 2002a) to 6 – 18 percent of the value of total annual cereal production in the country (World Bank, 1996a; MOA, 2002a).

3.5 The causes of land degradation in Eritrea

Understanding the process of land degradation and identifying the major factors that give rise to it are important preconditions for policy making in respect to NRM. The factors that directly cause or accelerate soil erosion in the highlands of Eritrea include deforestation, inappropriate land management practices, overgrazing and the use of dung and crop residue for fuel. Other factors that indirectly contribute to land degradation include high population pressure, insecure land tenure, poverty and war. These factors will be discussed below.

3.5.1 Direct causes of land degradation

Deforestation

Forest cover provides land with protection from the direct impact of rainfall. It enhances the availability of organic matter in the soil, and contributes to soil strength by providing additional cohesion (Cassels *et al.,* 1987). Thus, deforestation does not only expose soils to the direct impact of rainfall but makes soils easily erodible by reducing organic matter content and water holding capacity. This reduces infiltration rate and increases run-off and soil erosion.

Massive removal of vegetative cover is the major driving force behind Eritrea's land degradation in general and soil erosion in particular. In the mid nineteenth century about 30 percent of the country was covered by forests. However, by 1951, the forest cover had declined to 11 percent of the total land area of the country. Today, most parts of the country are almost devoid of trees, with forests covering only 0.8 percent of the total land area (FAO, 1994).

Population growth has increased the demand for cropland, grazing land and wood for construction and fuel. These factors have been instrumental in causing massive deforestation in Eritrea. As shown in Table 3.9 soil loss from croplands in Eritrea is 21 tons per hectares per year, while soil loss from forested areas is only 1 ton per hectare. The considerably higher rates of soil loss from non-forested land use systems relative to those from forest area clearly shows the negative effect of deforestation on land degradation in general and soil erosion in particular.

Inappropriate land management practices

Farmers' land management practices such as the kind of tools used, crops grown, timing of sowing, crop rotation, the use of fertilizer and expansion of croplands with increasing demand for food crops have all had some effect on land degradation.

Crop production in the highlands of Eritrea is characterized by the dominance of annual crops, mainly cereals. The major crops grown in the country are sorghum, barley, wheat, taff and maize. Although some perennial crops such as fruit trees are also produced in the highlands of the country, these crops constitute for a small proportion of the total area cultivated. The dominance of annual crops rather than perennial crops in the highlands of Eritrea implies the presence of very little land cover for the croplands during most periods of the year.

Expansion of agricultural land into marginal lands is usually induced by population pressure. Such expansion is often cited as a major cause of land degradation, particularly soil erosion, but available statistics show that Eritrea's harvested area increased from 1950 to the early 1960s and then declined considerably (MOA, 1993). The country's 30-year war of independence, which started in 1961, is the main reason in fluctuation in the cultivated area. However, despite the absence of evidence of recent expansion of croplands to marginal lands, the fact that steep slopes are currently cultivated in many parts of the highlands of the country suggest that agriculture has already been extended to marginal lands.

Eritrean farmers use farming practices that help reduce land degradation. These practices include fallowing, crop rotation, intercropping, application of manure and rotational grazing. In addition, they use practices such as terracing with the specific objective of soil and moisture conservation. However, due to increasing population pressure and the consequent acute shortages of croplands and firewood, fallows have become shorter and the amount of manure is inadequate.

Burning of dung and crop residues

The use of dung and crop residues as fuel means that Eritrea's soil is deprived of its traditional sources of nutrients. In addition, as their organic matter content decreases, soils become easily erodible. With the decline in the availability of firewood, the burning of dung and crop residue has become more common, particularly in the rural areas. Almost all the domestically produced dung is used for fuel. In addition, a considerable proportion of the dung that falls directly on croplands as well as crop residues, particularly those of maize and sorghum, is collected for the same purpose.

There is no reliable estimate of the extent of the use of dung and crop residues as a substitute for firewood in Eritrea. Newcombe (1989) estimated that about 90 percent of the total dung production in Eritrea is used as fuel. However, the approach he used required restrictive assumptions and hence his figures should be considered only as a rough approximation. He estimated the extent of the use of dung and crop residues for different regions of Ethiopia (including Eritrea) indirectly from estimates of fuelwood deficits in respective areas. He then used hypothetical fuel mixes of dung and crop residues for different regions, which, in turn, were used as a substitute for the estimated fuelwood deficit in the respective regions (Bojo and Cassels, 1995).

Based on the assumption that per capita consumption of dung for fuel in Eritrea is the same as in neighbouring Ethiopia, Bojo (1996) estimated that about 20 percent of the total dung production in the country was used as a substitute for fuelwood. However, the figure is likely to understate the extent of dung use in Eritrea as per capita dung consumption is likely to be higher than in Ethiopia where firewood is less scarce.

FAO (1997) estimates that dung and crop residues respectively constitute for 8.3 percent and 1.6 percent of the total energy demand in the country. Despite the lack of precise data, the use of dung and crop residue for fuel in Eritrea is very high and one of the major factors underlying the problem of land degradation.

Overgrazing

Crop production in Eritrea is almost entirely dependent on the use of oxen for ploughing. Moreover, Eritrean farmers are not self-sufficient even in good years (MOA, 1993; Riely, 1995) and face a high risk of crop failure due to lack of rainfall or crop infestation. Thus, they tend to keep as many livestock as possible to supplement their income and as security against crop failure. Besides economic considerations, ownership of a large number of livestock is considered as a sign of wealth and prestige.

The number of livestock is much higher in the lowlands of Eritrea than in the highlands with the former accounting for more than 60 percent of the total livestock population. The average tropical livestock unit (TLU) per household varies from a minimum of 1.45 in some areas of the highlands to about 7.85 in the lowlands[9] (FAO, 1994). Table 3.10 shows that the total number of livestock in the country is considerably higher than the carrying capacity of the land in five of the six regions. The difference between the carrying capacity and current levels of livestock is much higher in the Central Highlands than in the other regions.

Table 3.10 TLU and carrying capacity by region in Eritrea in 1997

Region	Total Area* Km^2	TLU**	TLU/km^2	Carrying Capacity*** TLU/ km^2
Anseba	23,200	283,746	12.23	8
Debub	9,300	581,346	62.64	16
Gash Barka	33,200	1,085,579	32.70	16
Maekel	1,080	58,040	53.79	16
Northern Red Sea	27,800	408,267	14.68	8
Southern Red Sea	27,600	189,458	6.86	8
Total	122,180	2,606,436	20.9	

*Reliable land areas are not as yet available for Eritrea and the total differs from the often quoted figure presented in Chapter One.
** based on a conversion factor of 1, 0.7, 0.1, 0.5, and 1 for oxen, cattle, sheep/goats, donkeys and camel respectively.
*** The carrying capacity is estimated based on 6 and 12 hectares per TLU in the higher and lower rainfall regions respectively.
Source: Based on Table 3.4, Table 5.1, and FAO (1997)

Overgrazing is, therefore, a serious problem in the Central Highlands of Eritrea; and a shortage of animal feed, particularly in the dry season, forces the migration of livestock to the eastern escarpments or the south western lowlands. Inadequate nutrition ranks next to endemic diseases as the second major constraint to livestock production in the country (FAO, 1994). The production of dry matter from most grazing land is lower than what rainfall and climate permit

[9] One TLU is equivalent to one 250 kg cow or four 50 kg goats.

mainly due to poor management of grazing land. Many areas are reported to have lost their original vegetation and to have been invaded by nutritionally inferior grasses (FAO, 1994). The compaction of soil from trampling by livestock also increases the risk of soil erosion by reducing the rate of infiltration destroying the aggregate stability of the soil and reducing its water holding capacity (Jahnke, 1984). The qualitative assessment that overgrazing is the major cause of land degradation in the region (Catterson, 1995; FAO, 1994), has not been tested by quantitative estimation of the extent of the problem nor a measurement of the actual loss of productivity from it are available for Eritrea.

3.5.2 Indirect causes of land degradation

In addition to the factors that directly cause land degradation, other factors also cause or accelerate land degradation indirectly by influencing land use and land management practices of farmers. Factors that influence farmers' land use decisions and their willingness and ability to invest on fertilizer, soil conservation and tree planting include land tenure, population growth, poverty and war. Lack of credit, extension and other services may also be important factors that influence farmers' land management practices. The relationships between land tenure, population growth and poverty on the one hand and land degradation on the other are discussed in Chapter two. In this section we will describe the land tenure system in Eritrea, the size and distribution of the population, and the nature and magnitude of poverty in the country. Finally, we will briefly discuss the effects of war on land degradation.

Land tenure

Land ownership and property relationships in the highlands of Eritrea are varied and complex. They encompass state, individual, family and communal (village) ownership. With the new land policy, all land and natural resources in Eritrea belong to the state and all citizens of the country are entitled to usufruct rights to agricultural and/or residential land (proclamation No. 58/1994). However, the new land policy has not yet been implemented and the traditional land tenure systems are still in practice. The three main types of land tenure – the *Diesa* system, family ownership and state ownership – are briefly discussed below.

The diesa system

This is the predominant system of land tenure in the highlands of Eritrea. In the *diesa* system of land ownership residents of a village, not necessarily related to each other by family ties, collectively own the land surrounding the village. While grazing land is used communally, croplands are redistributed periodically among married adult residents of the village by drawing of lots. The period of redistribution varies from village to village or sometimes within a given village depending on the crop rotation system practised in the village.

To ensure equity, the village cropland is classified into three grades: good medium and low quality. Every member of the community who qualifies for an allocation receives land from each category. To qualify for the allocation, the applicant must be a married male member of the village[10]. Widowed women can retain their husband's rights and divorced women take half of their husband's share. With the traditional *diesa* system land is distributed in such a way that all households (except a one person household which gets half the full share) receive the same size of land. However, in some villages, the Derg (the former Government of Ethiopia) introduced a system of land distribution where land is distributed according to family size. Once land is allotted, the household has the right to cultivate or lease it until the next redistribution. The holder, however, cannot sell or transfer his land and should he or she abandon the land for any reason the land is brought back to the pool from which individuals who qualify for land before the next redistribution are given temporary plots to cultivate (see Chapter Five)

Family ownership

This is believed to be the earliest form of land tenure system practised by the original settlers of the highlands of the country. This is a system of land ownership where all the landowners are descendants of a common ancestor who once owned the land. This system of land ownership is referred to as *risti*. Two types of *risti* exist. The first type refers to the system where members of the family are given only a usufruct right while the land is kept as their collective property. The second type refers to hereditary ownership where land is continuously divided and subdivided among the sons, and some times the daughters. This type of *risti* is known as *tslmi* and gives absolute ownership. Due to land reform programs by the former Ethiopian government as well as the two liberation fronts (ELF and EPLF), which converted the *risti* and *tsilmi* land tenure system in many villages into *diesa*, the former systems are not common these days.

State ownership

As the name indicates this type of land tenure system refers to land that belongs to the state. Such lands, also referred to as *dominale*, are lands where no one has a clear claim of ownership or lands where ownership or entitlement has been

[10] Currently there are some changes in eligibility for land. Some villages allow members who completed their national service to get land even before they get married.

abrogated for political or public utility purposes. These lands include forest, grazing and crop lands in all of the coastal and western lowlands and some areas in the highlands. They are also found in the southern areas of southern highlands around Asmara (the capital city) and the eastern escarpments. State lands are given as concessions to individuals who have the resources to develop them. The terms of the concessions, while renewable vary from 20 to 50 years (FAO, 1994).

Land tenure and land degradation

As noted already, the Eritrean highlands are dominated by communal ownership of land through the *diesa* system. This type of land tenure is considered as the major factor discouraging investment in land improvements thereby leading to land degradation (GOE, 1994). It is argued that the length of period of land redistribution (5 to 7 years) is too short to justify investments in land improvements such as terracing and tree planting that have a long gestation period. In addition, as croplands are open to common grazing during the post-harvest period, farmers cannot plant trees on their croplands. Crop residues that could otherwise provide ground cover and nutrient recycling are also completely removed. Communal ownership also precludes the possibility of using land as collateral. This makes it difficult for farmers to obtain credit to improve their farming activities. Finally, young members of a village who qualify for land (as they get married) have to be accommodated. This leads to a continuous reduction in household farm sizes as the village land has to be shared by a larger number of households. As a result farmers are forced to look for off-farm jobs to supplement their income, which leaves them with little time to invest in land improvement.

On the other hand, despite the belief that a communal land tenure system hinders investment in land improvement, land management practices in the highlands of Eritrea where communal land tenure is practised reflect a concern for natural resources. Traditionally arranged fallow periods are also in use in Eritrea's highlands and individuals cannot cultivate in areas declared fallow. Crop rotation, which is an environmentally friendly way of controlling pests and re-establishing soil fertility and thereby reducing soil erosion, is also widely practised by these communities. Cutting of live trees is totally restricted and a forestry guard is appointed to safeguard forest and grazing areas. Nadel (1946) remarked that Eritrean farmers made extensive use of terracing where their farms were located on sloping ground and that the terraces were well built and maintained. He disputed the argument that farmers on communally owned land could not show any interest in developing their land because of frequent changes in ownership. He stated that "the spirit of communal responsibility in these communities makes the temporary land holder work in the interest of his successors as well, since they belong to a closely knit social unit. The rules of fallow lying and the building and upkeep of terraces which outlive individual tenure, prove this communal spirit convincingly" (Nadel, 1946:4).

There are only few empirical studies that analyze the effect of private ownership of land on the management of natural resources in Eritrea. Tikabo (2003) analysed the effect of length of rental contract between landowner and tenant (which he used as a proxy for tenure security) on the probability of manure application (considered as long-term investment) and the extent of manure application. He found that the probability of manure application was higher on longer duration rental agreements than on a shorter duration rental agreements. On the other hand, the intensity of manure application was not different between short and long duration tenure arrangements. Interestingly, he found that the intensity of manure application was highest in medium duration tenure arrangements. This, the author argues, shows that tenure insecurity may even be a motive for higher application of manure because tenants may want to ensure continuity of operating the rented land by investing on the land.

Araya (1997) also analysed the effect of land tenure on soil conservation activities of farmers in the highlands of Eritrea. The study shows that farmers in areas where land is communally owned spend less time on soil conservation compared to those in areas where land is privately owned. However, time spent on undertaking soil conservation activities on owner operated land and rented land (a proxy for tenure security) do not differ significantly. While private ownership of land (*tslmi* and risti) is free of most of the problems associated with communal ownership discussed above, there is no clear evidence that land degradation is less severe in areas of private ownership. Steep farms with high risk of soil erosion are cultivated in these areas without any conservation measures. Disputes on land rights and boundary conflicts are also more common in areas where land is privately owned than where it is communally owned.

Population growth and distribution

As discussed in Section 2.2, population density varies considerably in the highlands and lowlands of Eritrea. The average population density for the highlands of Eritrea is 131 persons/km^2 compared to an average population density of 13 persons/km^2 for the lowlands. Average rural population density for the highland areas of the country is 73 persons/km^2 compared to a national average of 23 persons/km^2. Within the highlands, as well, population density varies substantially from one region to the other. Areas with higher agricultural potential generally have higher population density. Population densities for the different subregions of the highlands are discussed in Chapter five.

There are no current census figures for Eritrea. Despite questions about exact population size and growth over time, however, it is clear that population has dramatically increased in the last 50 years of the past century. The average rate of population growth is estimated to be 2.9 percent per year. FAO (1994) suggested that population growth in Eritrea could be even higher because of a possible post-war baby boom.

Rapid population growth and high population density are mentioned as factors that contribute to land degradation problems particularly in the highlands of the country. Population increase has led to expansion of agricultural lands to marginal areas and fallow periods got shorter leading to deforestation and soil erosion (MOA, 2002b). The theoretical links between population growth and land degradation are not always straightforward and are discussed in Chapter two.

Poverty and land degradation

The majority of Eritrea's rural people is poor. The nature and magnitude of poverty vary between rural and urban areas as well as among the various regions of the country. Poverty is generally concentrated in rural areas with about 67 percent of the poor living in rural areas. This group of people is highly dependent on low input agriculture and animal herding for their livelihoods. Due to lack of diversification in their incomes they face high-income risk and high frequency of food insecurity. They also lack access to most physical and social infrastructures. Urban poor on the other hand mainly depend on wage labour and petty trade. They have relatively better access to physical and social infrastructures (World Bank, 1996b; GOE, 2004b).

Table 3.11 Population below the poverty line in Eritrea*

Poverty incidence (head count)						
Location	Population		Poor		Extremely poor	
	Million	(%)	Million	(%)	Million	(%)
Rural	2.45	68.8	1.58	64.64	0.95	38.90
Urban	1.11	31.2	0.78	70.32	0.36	32.65
Overall	3.56	100.0	2.36	66.40	1.31	36.97

* The poverty line is Nakfa 240 per capita/month; Extreme poverty line is Nakfa 150 Nakfa per capita/month.
Source: After GOE (2004b)

Agricultural potential in general and climatic conditions in particular largely contribute to regional distribution of poverty. Poverty is more pervasive in the semi-arid lowlands where about 36 percent of the population live. However, the majority of the poor people live in the highlands of the country. The rural population in arid areas of the country mainly depends on livestock herding and where rainfall is adequate they grow some crops. However due to frequent droughts they are forced to sell livestock to buy food crops. The fact that many of the poor in this region are nomads also limits their access to health care and educational services. In the highlands, shortage of land and poor access to farm inputs such as seed and animal power are the major factors to high levels of poverty. Access to off-farm jobs is limited both in the highlands and lowlands (GOE, 2004b).

The theoretical links between poverty and land degradation are very complex and are discussed in Chapter two. It has already been mentioned that high dependence of rural population on the natural resources in their surrounding has led to land degradation such as soil erosion and deforestation. But it is not clear if poorer households do cause more damage to the environment than better-off households. There is no study that relates poverty and land degradation in the country. However, it is clear that the generally poor condition of the rural population contributes to land degradation because the rural population lack resources to invest on land, and do not have access to alternative sources of energy.

War and land degradation

The extended war for Eritrea's independence has had a considerable direct and indirect impact on the country's agrarian systems and thereby on the country's environment. The direct impact on land degradation in Eritrea includes the clearing of forests to supply the army with firewood and fortification materials as well as to improve visibility in war operations.

The war's indirect impact on land degradation includes its effects on the lives of the people, their property and their farming activities. Although no hard data are available on the change in the economic status of the rural population as a result of the 30 years war, there is no doubt that it has worsened. The country's labour force decreased significantly as many of the adult population joined the freedom fighters or migrated. The general threat to movement such as harassment, mines and aerial attacks also had a serious impact on economic activities to the extent that considerable proportion of the land was left idle. The war has also contributed to a high proportion of female-headed households in the country with most rural families having insufficient labour and other resources to undertake basic farming practices, let alone conservation activities.

In some areas, the war could have helped to reduce the problem of land degradation. The pressure on land was alleviated as the number of livestock decreased and the land was left idle. It has been observed that in many areas, where movement of livestock and people was restricted or unsafe, the natural vegetation has regenerated to form sufficient cover for the land.

Generally, however, the protracted war in Eritrea had an adverse impact on the environment. The apparently reduced pressure on resources in some areas was more than offset by increased pressure in other areas as people and livestock had to migrate to the relatively safer areas. Moreover, while the harmful effects of the war on the environment were direct and immediate, the factors that have a beneficial conservation effect were indirect and long-term in nature.

3.6 Summary

This chapter describes the precarious conditions of the rural population in Eritrea in general and in the Central Highlands in particular. The present conditions of the agricultural and energy sectors are described and the linkages between these sectors and the problem of land degradation are highlighted. High population density, rugged topography, erratic rainfall, traditional farming practices that make little use of external inputs and land degradation result in a low and declining agricultural productivity. Farmers in the Central Highlands of Eritrea try to meet the subsistence requirements of the growing population by expansion of cultivated land to fragile steep-slope areas and by shortening of fallow periods – a traditional method of restoring land productivity. As a result of this and the topographic and climatic conditions, the Central Highlands suffer from a severe land degradation problem. The energy sector also constitutes another key link between the economy and the environment. Biomass fuels such as fuelwood, dung and crop residues are the major sources of domestic energy in Eritrea. The use of wood for fuel and construction of traditional houses as well as the expansion of croplands has made most parts of the Cetral Highlands devoid of any vegetation. Dung and crop residues are almost exclusively used for fuel and animal feed depriving croplands from traditional sources of nutrients.

Soil erosion, nutrient depletion and deforestation are the major types of land degradation in the country. Various public projects in the form of Food for Work and Cash for Work programs, mobilization of students and other extension activities are underway to restore and/or prevent further deterioration of the environment. The government is also making efforts to increase agricultural productivity, among other things, by distributing seeds and chemical fertilizers at highly subsidized prices and often on credit, as well as by provision of tractor and extension services. Socio-economic, institutional and political conditions, however, hinder the adoption of new technologies by farmers and the success of the public projects.

Chapter 4

Model Structure and Approach

4.1 Introduction

Farm household modelling approach is a widely used tool of analysing the economic behaviour of rural smallholders. It has been used to evaluate the impact of various technologies and policy interventions on rural economies of developing countries.

The major problems that characterize the Central Highlands of Eritrea - poverty, food shortages and land degradation – cut across various disciplines requiring an interdisciplinary approach to address the problem. Bio-economic modelling, which allows simultaneous examination biophysical and socio-economic dimensions of the problem can be a useful tool for such an interdisciplinary analysis.

In this chapter, we will first discuss theoretical foundations of the farm household modelling. Next, we will briefly discuss different bio-economic models (BEMs). Finally, the basic structure of our bio-economic model (Chapter six) will be described and various components of the model will be discussed.

4.2 Theoretical foundations of farm household modelling

Traditionally economists used to consider rural households as typical business firms and applied the profit function to explain decisions regarding production and resource allocation. Microeconomic theory shows that in a perfect competition setting firms will employ inputs until the marginal value product of an input is equal to input price. Since both inputs and outputs can be purchased at the market price, the levels of employment of inputs are not influenced by the entrepreneurs' resource endowments. Similarly, consumptions preferences of households do not have any bearing on production decisions.

In rural areas of developing countries production decisions of the household influence its consumption choices. In consumer theory, the consumer maximizes utility under given set of prices and fixed income. In farm-household models, on the other hand, household income, which includes farm profits is endogenous and depends on the production decisions of the household. As a result policies that affect commodity prices may have different impact on household consumption when consumption and production decisions are considered simultaneously than when only the consumption side is taken into account. For example, in the standard consumer theory, when the price of a normal good increases the negative "income effect" reinforces the negative "price effect" and results in unambiguous decline in the consumption of the commodity in question. However, since rural households engaged in the production of the commodity will enjoy higher income from higher price of the good (termed as profit effect), there will be a positive "profit effect". Thus when the production and consumption decisions of the farm household are taken into account, the net effect of an increase in price may be positive or negative (Singh *et al.,* 1986; Taylor and Adelman, 2003).

When perfect inputs and outputs market exist, there is only one-way link from production to consumption (as discussed in the above paragraph). As households can buy and sell commodities at the market price their consumption decisions will not influence the level and composition of their output. Similarly, as labour can be freely bought and sold in the market, the amount of labour households use in production depends neither on the labour endowment of the household or the decision of the household to allocate family labour between work and leisure. In this situation, the farm-household's objective can reasonably be taken as maximization of profits.

However, rural economies in developing countries are characterized by imperfections in input and output markets and credit and liquidity constraints. The absence or imperfection of output market means that households can only consume their own output (when the good is not traded) or they choose to consume own produced good to market-purchased good (because of high transactions costs). In this case, farm profits include implicit profits from goods produced and consumed by the same household. Similarly, household decisions on the allocation of labour influence its production decisions. Since labour markets are thin, a decision by the household to consume more leisure means less labour for crop production and hence a decline in production. Rural households also largely depend on their own sources for other non-labour resources as they have no or little access to credit. Thus, the proposition that profit maximization is the main objective of the farm household does not hold. Production decisions of the farm household are influenced by its consumption and labour allocation decisions (Singh *et al.,* 1986; de Janvry *et al.,* 1991; Delforce, 1994).

Thus, when the assumption of separability of production decisions from consumption and labour allocation decisions do not hold due to absence or imperfection of input and output markets, the need to meet subsistence needs from farm produce, liquidity problems etc., a non-separable farm-household model that simultaneously considers production and consumption decisions is needed to understand the microeconomic behaviour of farmers and to evaluate the relative merits of alternative policies and technologies.

4.3 Bio-economic modelling approaches

From the 1980s, the concept of sustainability was high on the agenda of researchers and policy makers. But there were serious difficulties to define and operationalize the concept. The most widely quoted Brundtland Commission defines sustainable development as one “that meets the needs of the present without compromising the ability of the future generations to meet their own needs” (WCED, 1987: 103). Barbier (1987:103) states that sustainable development is an economic development with the primary objective of “reducing the absolute poverty of the world’s poor through providing lasting and secure livelihoods that minimize resource depletion, environmental degradation, cultural disruption, and social instability”.

Operationalizing the concept of sustainable development is an even more challenging task. Sustainable development has several dimensions that incorporate economic, social and ecological goals that may complement or conflict with each other. In the 1980s, bio-economic models were developed to operationalize the concept of sustainable development. These models integrate the socio-economic component related to household behaviour, market structure, institutional arrangements and policy incentives and environmental component such as soil erosion, nutrient depletion, crop and animal growth etc. Bio-economic models are helpful tools to explore the complex interactions between agro-ecological and socio-economic phenomena and make it transparent for policy debates (Kruseman, 2000).

4.3.1 Classification of bio-economic models

Bio-economic models can be classified into different categories based on different criteria such as a) emphasis on biophysical component or economic component, b) time scale, c) level of aggregation.

Bio-economic models vary in terms of their emphasis on the economic or biophysical components in the model. Brown (2000) identifies the following categories: i) biophysical processes models to which an economic analysis component is added; ii) economic optimization models that include a biophysical component; iii) integrated bio-economic models.

Biophysical models are primarily designed to simulate agro-ecological processes involved in various systems such as crop production, livestock, agroforestry and soil and nutrient. Such models may be a detailed description of a single component or model the major inter-linked components of a particular ecosystem. Most biophysical models also incorporate some socio-economic issues and accounting equations that enable to calculate the benefits and costs of alternative scenarios.

Economic optimization models that involve decisions related to production and resource use cover a wide range of models that differ on the way the biophysical components are included in the model. Some economic optimization models take a simplistic approach in which the model basically optimises farm income but includes some biological equations that measure the sustainability of the system being modelled. Others are more complex in that they attempt to account for the possibility of multiple objectives (economic and sustainability) by taking into account the dynamic relationships through the use of multi-period modelling approach. Barbier and Carpentier (2000) distinguish two ways in which environmental problems are included in BEMs. The most common way is to simulate the effects of economic decisions on the environment without taking into account the feedback effect of the change in the condition of the environment on the production function of the model. The second and more difficult way is to model the feed back of natural resource degradation on agricultural production. Integrated BEMs refer to the later type of models in which the economic features of economic optimization models and the biophysical processes are adequately taken into account.

The issues of rural poverty, food security and NRM involve intertemporal decisions. The aim of the study influences the temporal period to which a model refers. Depending whether the aim behind developing a model is descriptive, explorative or planning (predictive), a static (one year) or dynamic (multi-annual model) can be developed. The choice of static or dynamic models also depends on whether the objective of the study is to explore adoption process and welfare and environmental processes or just the total potential impact of new technologies and policies (Kruseman, 2000; Holden, 2004).

Bio-economic models also differ in the level of aggregation at which the study takes place. They may be constructed at different levels such as field/plot, farm/household, village, watershed or region. As stated earlier, BEMs may emphasize biophysical aspects or socio-economic analysis and the criteria used for selection of the level of aggregation vary between different disciplines. From the viewpoint of economics, the level at which decisions are made is the most appropriate level to build a model (Kruseman, 2000). Holden (2004) provides a typology of village economies, which could be used as a basis in selection of the level of aggregation. The major factors to be considered are a) the degree of differentiation in resource distribution and specialization of activities within a village and b) the extent to which the village is integrated in or isolated from the outside markets (i.e., the transaction costs involved). In cases where the village is isolated from outside markets (e.g. no linkage to an external labour market) and distribution of resources within village is uniform, a single farm household model may be sufficient. However, if resource distribution among households is significant, a model with several interacting households may be necessary.

Okumu *et al*. (2000) maintains household level assessment of production and conservation technologies could be too restrictive because it ignores the natural delineation of the landscape and hence the biophysical scale of the problem as well as the importance of community participation in solving general externalities arising from household agricultural production. It is argued that aggregation of household decision making at a village or watershed level could be better alternatives particularly in situations where community level management of resources is in place.

Village or watershed level models, however, have their own shortcomings associated with aggregation. Socio-economic variations within the village are ignored due to averaging of resource availability (Holden, 2004; Okumu *et al.,* 2000). Brown (2000) also maintains that models that fail to explicitly include variations in resource endowments tend to mask issues related to food security and NRM. It is argued that policies often have different impact on different groups of households that even when overall welfare is optimised, there will be some winners and losers. Both the effectiveness of various interventions in terms of their economic and environmental effect and the likelihood of their adoption depend on who is directly affected (Shepherd and Soul, 1998; Brown, 2000). Thus, even higher-level models should include households of various resource endowments.

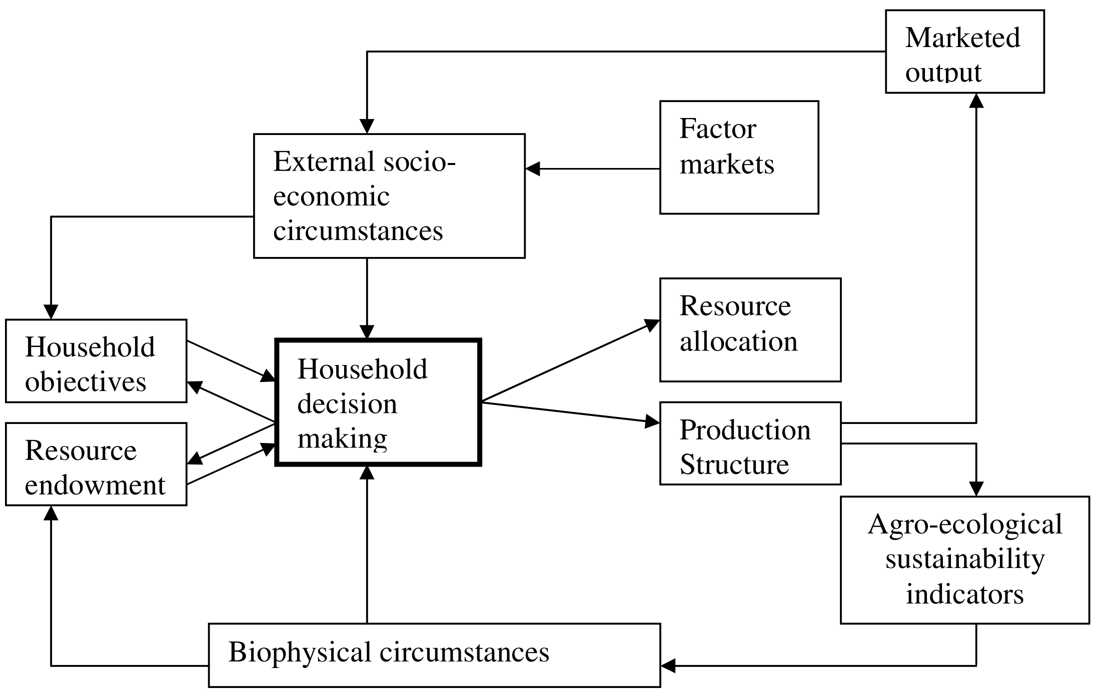
4.4 The structure and major components of the BEM of the farming system in the Highlands of Eritrea

This study develops a village level dynamic mathematical model of production and conservation decisions (see Chapter six). The model maximizes aggregate discounted future stream of net income subject to a large set of constraints (see next section). As in most developing countries, consumption and production decisions are interrelated in rural areas of Eritrea. This is taken into account in the model by including resource constraints and constraints reflecting the need to meet a minimum consumption requirement. The reason for selecting the village rather than the household as our unit of analysis is based on a number of factors. First, land is communally owned in all the study villages and the decision on the allocation of the land among various uses is made by the community. Second, grazing lands and woodlands are used communally and even croplands are open for common grazing after each harvest. Third, land degradation problems such as deforestation and soil erosion occur at a larger scale than the individual farm. The methods to reverse or curb the problems are more effective if undertaken at a larger scale than at the individual farm. Finally, members of the villages in Highlands of Eritrea have close family ties and share key agricultural resources among themselves. Therefore, resource constraints are not as binding at the farm level as they are at the village level[11].

4.4.1 Structure of the bio-economic model

Household decisions are influenced by household resource endowments, household objectives, existing market and policy environment as well as biophysical characteristics.

Figure 4.1 Household decision-making



Source: Based on Kruseman (2000)

[11] As discussed in the previous section village levels have their own limitations. Thus, for the purpose of comparison, a household-level model that distinguishes between poor, less poor and non-poor households is developed. The results of the village and household models are compared to evaluate the impact of the choice of the scale of analysis (see Section 8.6).

These decisions, in turn, affect the economic conditions of rural households and the biophysical environment on which they depend. Figure 4.1 shows the main factors that influence land use and resource allocation decisions that form the basis of the bio-economic model developed in Chapter six.

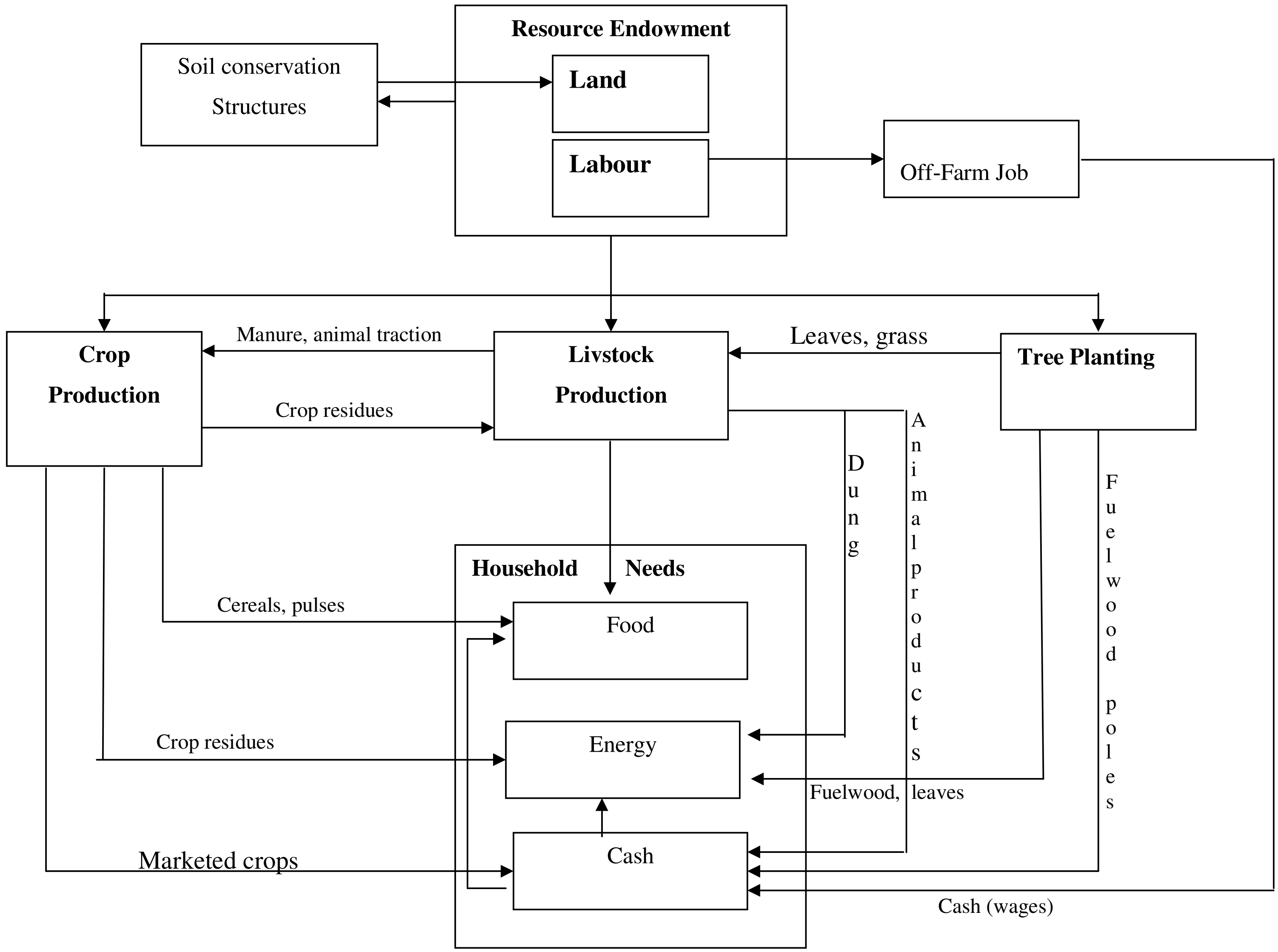
4.4.2 Interactions between various components of the model

Central element in developing the model is the interdependence of the economic activities in which the rural people are engaged and the linkage among those activities, as well as the relevant NRM (or farming) technologies and their linkages with the economic objectives and the state of the natural resources. The interdependence of the various economic activities of the rural population is mainly due to the following reasons.

1. All economic activities and soil conservation practices compete for the limited resources of the farmer such as labour and land. Rural households have a limited area of land (with different land categories) at their disposal, which has to be allocated to crop production, grazing, tree planting (or natural woodlands), or soil conservation structures.
2. The output of one economic activity serves as an input to the other economic activity. E.g. crop residues are used as animal feed; animal dung and animal power are used as inputs in crop production. Leaves from trees serve as animal feed and the availability of more trees provides sufficient fuelwood so animal dung can be used as fertilizer in crop production.

Figure 4.2 shows the linkages between household resource endowment, household objectives and the various economic activities.

Figure 4.2. Linkages between household resource endowment, household objectives and the various economic activities



4.4.3 Socio-economic components of the bio-economic model

Since farmers make decisions, socio-economic conditions that surround household decisions are as important as biophysical conditions in terms of their effects on both rural income and resource conditions. Socio-economic components included in this study include household goals and objectives, resource and other constraints, and economic activities such as crop production, livestock production, and tree planting. We will briefly describe these components below.

Household goals

Although farmers in the highlands of Eritrea depend on the market for many basic goods that cannot be produced on the farm, they produce at or near-subsistence level so that their major objective can be better described as securing basic needs from the farm than profit maximization. Thus, the dominant objectives of a representative household include securing sufficient food (cereals and pulses) for the family and sufficient energy for cooking. Farmers also strive to generate sufficient cash for the purchase of important non-farm items (such as clothing, kerosene for lighting, stationery and school fees, transportation etc). Farmers in developing countries often reduce risks by diversifying their agricultural activities. In the Central Highlands, this is reflected in the combination of crops farmers grow as well as the diversification of their activities on crop production, livestock and other non-farm activities. For this reason, we will include diversification of income in the socio-economic objectives of the farmer. Subject to the above conditions, farmers will maximize their net-discounted income from their farm and non-farm activities.

Crop production

Various types of crops are grown in various parts of the Central Highlands of Eritrea. These crops include cereals such as barley, sorghum, wheat, millet and taff as well as pulses such as beans and chick-peas (see Chapter two). The model allows selection from five crops each in the three study villages. Potatoes can also be produced in the irrigation scenario. Crops can be grown on three land types using two options of land management (with and without stone bunds) and six types of fertilizers, which include inorganic fertilizer, manure, mulching and/or some combinations of them.

The production function in the linear programming model represents the average expected response to different types and levels of fertilizer application, mulching and the construction of stone bunds. The production functions are specified for each type of crop, each village, and each type of soil type (see Chapter seven).

Livestock activities

Cattle, donkeys, sheep and goats are the major types of livestock in the study area. The composition of livestock farmers choose is dictated by a number of considerations including the need for animal power, availability of animal feed, the availability of labour and cash. The choice of the number and composition of livestock, in turn, determines the income flow from this activity.

The model simulates the size and management of herds of each type of livestock. Herd growth is determined by natural growth (birth-mortality), and the buying and selling decisions of households. Each type of livestock unit requires labour time, veterinary expenses and forage throughout the year. Feed requirements for livestock are defined in terms of dry matter. Animal feed may have its source from grazing land and woodlands within the village, cut and carry from woodlands where grazing is not allowed, or from crop residues. Livestock in two of the three villages may also migrate to the eastern escarpments in certain months of the year.

Oxen are used for land preparation, donkeys for transportation and cattle and sheep/goats for producing milk and meat. Livestock can also be sold to generate cash.

Tree planting

The model considers two types of woodlands: native woodlands and eucalyptus plantations. Native woodlands are established by simply restricting the area from cultivation and grazing. Thus labour required to establish these woodlands is insignificant. Eucalyptus plantations, on the other hand, require considerable amount of labour. The volume of wood on woodlands is a function of the existing volume of wood, natural growth (yield) and wood harvest. Yields of wood vary by land type and land management (construction of stone bund). The yields of wood from eucalyptus plantations are much higher than that from native woodlands. Trees can be harvested 5 years after planting. When trees are cut the land may be replanted with trees or converted to grazing or croplands.

Model constraints

Farming households make their decisions under various sets of constraints. The constraints in our model include limited availability of resources (land, labour and oxen), subsistence constraints, constraints relating to market conditions (such as prices of inputs and outputs and non-farm produced goods, access to credit, etc.), biological constraints (such as the relationship between fertilizer and crop yield, soil conservation and crop yield etc), and logical constraints such as specifying the amount of manure used for fertilizer and fuel cannot exceed the amount of manure produced in the farm.

In the Central Highlands of Eritrea, where little modern agricultural inputs and technologies are used, labour continues to be the most important input. Both the supply and demand for labour in the study area varies in different periods of the year. Thus, labour constraints are applied for each period. Demographic factors such as total number of households in a village, average family size, household age and gender composition, as well as cultural (religious) and schooling calendar were considered to determine labour availability in each period. Since some farming activities have to be particularly done by adult males, separate constraints are used for total labour supply and for the supply of adult male labour. Limits on the number of days rural households can have a paid off-farm job in each period were also imposed for each village, depending the distance of the study villages from major urban centres.

Land constraints are formulated by land type and by type of conservation. The area of land of a given type used for crop production, grazing and tree planting cannot exceed the total area of land of that type. Other resources such as cash, oxen, manure, and crop residues are endogenous to the model as they depend on farmers' decisions. However, the use of these resources in any given period cannot exceed their supply.

Constraints on subsistence needs were defined in terms of minimum calorie requirements. To reflect current consumption patterns only part of the calorie requirement can be obtained from cereal consumption. Constraints were also imposed to ensure that households have enough energy for cooking and lighting. Cash expenditure on all inputs and consumption goods cannot exceed the total amount of cash earnings.

4.4.4 Biophysical components of the bio-economic model

Biophysical conditions such as land quality and climate determine the suitability of a region to various economic activities and the potential production. Biophysical conditions are partly influenced by management decisions of economic agents who utilize them. Thus important biophysical possibilities and constraints and possible sources of data were identified.

Three regions were identified in the Central Highlands based on their agricultural potential, population density and market access condition. Three representative villages were selected, one from each region, for which land capability classification was made. The biophysical components that are of direct importance to our study include climate (mainly rainfall), land size, land type (including topography and soil depth), land use and land cover. Climatic data for the villages were collected from the nearest metrological stations. Land classification for the three study villages was made with the help of experts and four soil types were identified (see Section 6.4).

Soil erosion, nutrient depletion and deforestation are the major environmental problems in Eritrea which have a negative impact on crop yield and hence on the economic situation of the rural poor (see Chapter two). Thus the biophysical components of our bio- economic model include soil erosion, nitrogen balance, and vegetation components.

The rate of soil erosion is determined by climate, topography, land use, and land management practices. Soil erosion is calculated separately for croplands, grazing land and woodlands. Soil loss from croplands is a function of land type, crop, type of soil conservation and type of fertilizer applied. The rate of soil loss from croplands under different land management practices is estimated using the Technical Coefficient Generator developed for the highlands of Ethiopia (see Section 7.4). Soil loss from grazing lands and woodlands were modelled as a function of soil type and type of soil conservation applied. Long-term empirical data from experimental plots in Afdeyu Research Station were used to obtain soil loss from other land use categories. These data were extrapolated to soil loss from various land categories using the Universal Soil Loss Equation adapted to the Ethiopian conditions as shown in Chapter seven.

As in other parts of Sub-Saharan Africa, nitrogen is the most important nutrient that limits crop yields in Eritrea (Hubbell, 1995). Nitrogen balance in a given year depends on endogenous and exogenous sources and processes. The major sources of nutrient inflow are the application of mineral as well as organic fertilizers. Major mechanisms of nutrient removal, on the other hand, include the harvests of crops and residues as well as the washing away of nutrients from croplands due to soil erosion. An initial pool of nitrogen is estimated a certain fraction of which is mineralized and becomes available to crops each year. The stock of nitrogen in the soil and hence the amount of nitrogen that will be available to crops from endogenous sources declines over time at different rates depending on the type of fertilizer applied. This is discussed in Chapter seven.

4.5 Conclusions

The rural areas in the Highlands of Eritrea, as those in most developing countries, are characterized by absence or imperfection of input and output markets as well as credit and liquidity constraints. As a result rural households make their production and consumption decisions simultaneously. This means a non-separable farm-household model is required to explore rural household land use and land management decisions.

Due to the communal land tenure system in the study area important decisions are made both at a village and at household level. Moreover, rural household in the villages in the Central Highlands have close family ties and share key agricultural resources such as labour and oxen. Resources are therefore not as binding at the household level, as they are at a village level. Moreover, the problem of land degradation, a key issue in this study, occurs at a larger scale than the specific plot cultivated by a household and efforts to tackle the problem often include a community participatory management approach. Thus a village model is developed to explore land use and land management decisions in the study area.

Since low agricultural productivity and land degradation are the two major and closely related problems in rural areas of Eritrea, we develop a bio-economic model with economic and biophysical components. In this chapter, the linkages between the various components of the model and the major constraints are described.

Chapter 5

The Field Research

5.1 Introduction

The use of mathematical modelling to understand farmers' decisions and to explore the impacts of technological and policy changes on rural income and the environment involves the identification and estimation of a large number of socio-economic and biophysical parameters. Unfortunately, most of the data required are either not available or, when available, not at the desired scale. For example, an estimate of the average size of farm is available for the highlands of Eritrea, but not at the village level. As much as possible effort was made to collect data from secondary sources. However, due to decades of war no systematic and coherent set of data required to undertake a study of farmers' strategies was available.

Field research was undertaken to obtain parameters relating to household resource endowments and labour and oxen requirements for various activities as well as to explore cultural and institutional conditions that influence their decisions. Moreover, farmers' awareness of the risks of land degradation on their farms and their perception of the impacts of new technologies and land management practices such as the application of fertilizer and stone bunds is explored.

Field research for this study took place from April 2002 to March 2003 in various villages in the Central Highlands of Eritrea. The fieldwork involved household surveys, field measurements of the size of croplands, land type and land use classification of study villages, as well as estimation of biomass production from Eucalyptus plantations in the study area.

5.2 Methodology of the field research

Three subregions were first identified in the Central Highlands based on characteristics such as topography, market access and the availability of off-farm job opportunity. We refer to these three subregions as Zoba Debub East

(ZDE), Zoba Debub West (ZDW) and Zoba Maekel (ZM) based on their relative location in the Central Highlands of the country[12]. Then out of a list of all villages in the country prepared by the Ministry of Local Government (2000) three villages were randomly selected in each of the above mentioned subregions. In each village thirty farm households were, then, randomly selected for the general survey. So, in total 9 villages and 270 farm households were included in the general survey. In addition, three villages - one village in each of the three subregions - were again selected where in-depth interviews were undertaken with ten households. The objectives of the general and in-depth surveys as well as the type of information collected are described in the following sub-sections.

Three interviewers, two graduate assistants from the College of Business and Economics, of the University of Asmara, and one third-year student from the same university participated in conducting the surveys. Prior to a pilot testing of the questionnaire, the interviewers were given some training. All the questions were discussed in detail with the interviewers to ensure that they understand the questions properly. Then a pilot survey involving 20 farmers was carried out in two villages. This helped to test and adjust the questionnaire and to further train the enumerators. In total 270 questionnaires were completed.

5.2.1 General farm household survey

In the general household survey which was conducted in the 9 villages (three villages in each of Zoba Debub East, Zoba Debub West and Zoba Maekel)[13] information was collected on farm resources, the activities performed by members of the rural households, household consumption habits particularly with regard to food and use of energy, households' perception of the quality of their farms and erosion risk etc. Such information is to be used to determine the quantity and quality of resources households are endowed with, to describe the present production and consumption situations, which are important to deduce household objectives and factors constraining their decisions.

Whenever possible, we tried to contact the head of the household for an interview. However, due to the fact that a large part of the population were mobilized due to the border conflict with Ethiopia, this was difficult. Thus, when it was not possible to meet the head of the household, any adult member of the household was interviewed. If both the head of the household and his spouse

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[12] As the subregions cover large areas, the topography, market access and off-farm job opportunities vary within a given sub-region as well.

[13] The villages where the general survey has been undertaken are Mai Harasat, Hadida, Awlietsoru, Adi Baro, Adi Merkeja, Biet Gebriel, Ametsi, Zigb and Adi Qontsi.

(or any other adult member) were present, both of them were made to listen to the questions and both could respond.

5.2.2 In-depth farm household survey

Three villages, Maiaha, Zibanuna and Embaderho representing the three regions of ZDE, ZDW and ZM respectively have been selected for an in-depth study. Ten farm households from each village were included in this survey. The survey involved a physical measurement of the size of each and every plot cultivated by the respondents as well as detailed interview with the heads of the households. As the farmers had to guide the enumerators to all their crop fields, sometimes up to 6 kilometres apart, they were given a small financial incentive.

The detailed questions in this survey dealt particularly with inputs and outputs in crop production. Each household was asked to give a detailed description of each plot of cultivated land, including the frequencies of ploughing and weeding, the length of time each activity took, the amount of seed and fertilizer used and the production from each plot. This information was then combined with physical measurements of the size of each plot to determine the input-output coefficients (yields, labour input per hectare etc.) needed in the mathematical model developed in the next chapter. More detailed information was also asked on time allocation of households as well as cash expenditures made on crop and livestock activities.

5.2.3 Field measurements

In addition to the household surveys, the field research included some field measurements. The field measurements included the classification of land into various categories of land use and land capability, which was carried out by land use experts in the Ministry of Land Water and Environment and estimation of biomass production from eucalyptus plantations and natural woodland, which were carried out by senior students in the Department of Forestry, University of Asmara.

While secondary data on slope of land, soil depth and soil type, which determine the suitability of land for various kinds of activities, are available at a regional levels, such data are not available for most villages in Eritrea. Thus land use experts from the Ministry of Land Water and Environment helped to prepare land use and land-capability classification of two of the three villages (Maiaha and Zibanuna). Similar land classification was already available from the above ministry for Embaderho. The land capability classification is based on a widely used system of land evaluation developed by the United States Department of Agriculture. The classification is mainly based on soil depth and slope and indicates the extent of physical limitations of a given land to crop growth.

According to this system, land is classified into eight classes. For the purpose of our analysis, however, the number of land categories is reduced into four classes (Section 7.2).

Despite the fact that projects of afforestation have been undertaken in the highlands of Eritrea for decades, the rate of growth of various species of trees (or volume of wood produced per hectare) has never been monitored. This is mainly because the projects' objective was largely soil conservation and not production of wood (FAO, 1997). Thus, after consultations with the head of the Department of Forestry at the University of Asmara, we agreed that three senior students from the department would undertake their senior project on biomass yield of Eucalyptus plantations in the Central Highlands of the country under his supervision. The results are used to compare data obtained from secondary sources (Section 7.7).

The students took two sites in the Central Region (Zoba Maekel), which had been afforested since 1992 and 1993. The whole forest plantation areas in the two sites were divided into six plantation stands based on age. From each stand two representative blocks were selected. In each block the students took two sample areas of 300 m^2 and the number of eucalyptus trees in each sample area were counted. The diameter at breast height (dbh), total height and bole height of each tree were measured using diameter tape and telescopic stick. In addition, the physical condition of each block (slope and conservation measure applied) was recorded. Based on the above information the students could estimate, among other things, the mean annual increment of eucalyptus trees (Ermias *et al.,* 2003). The same students have also taken a case study of a certain permanent closure in the Zoba Maekel 16 km south of Asmara to estimate the biomass production of acacia woodlands in the Central Highlands of Eritrea. Research results from this study together with estimates from similar environments in the region will be used to estimate biomass production from eucalyptus plantations and natural woodlands.

5.3 The research area and the research villages

5.3.1 The Central Highlands of Eritrea

The Central Highlands of Eritrea cover areas with an altitude of 1500 meters and higher above sea level and average annual rainfall of 500 mm. This zone enjoys for the most part a warm to cool semi-arid climate and comprises a number of sub-zones that have common major crops but differ in altitude, annual precipitation, relief, soils, population pressure and degree of environmental degradation. According to past administrative classification, this zone comprises the three provinces of Akelguzai, Hamasen, and Seraye or according to the current administrative classification of the country, Zoba Debub and Zoba Maekel (which literally mean southern region and central region respectively) and a small part of Zoba Anseba. When we refer to the Central Highlands in this area we refer to the Central and Southern Zones only.

The number of households, the total land area per household and the cropland per household in the various sub-zones of the Central and Southern Zones are presented in Table 5.1. Zoba Debub consists of 12 sub-zones and 894 villages and Zoba Maekel consists of four sub-zones and 98 villages.

The Central Highlands cover a total area of approximately 1.01 million ha, which is 8.38% of the total land area of the country. The area under cultivation is 240,112 ha or 23.7% of the total. The total rural population is about 740,000 resulting in a population density of 73 persons per square km. This is much higher than the national average of 32 persons per square kilometre. The average total land and average cultivated land are 5.47 and 1.32 ha per household respectively.

Table 5.1 Land and rural population in the Central Highlands, 2000**.**

Sub-Zoba	Total area (ha)	Agr'l[14] land (ha)	Total population	Total number of households	Total land /hh (ha)	Agr'l land /hh (ha)
Zoba Debub	**928130**	**186150**	**598332**	**149752**	**6.05**	**1.24**
Adi Keih	57118	5903	42279	10414	5.48	0.57
Segeneiti	75226	9050	36663	9520	7.90	0.95
Tsorona	74600	8204	30352	7275	10.25	1.13
Dekemhara	42542	9600	44500	11118	3.83	0.86
Mai Aini	82300	11081	30713	7508	10.96	1.48
Senafe	121044	10601	84322	24604	4.91	0.43
Areza	135751	27885	62563	15043	9.02	1.85
Emni Haili	44166	17867	45757	12082	3.66	1.48
Adi Quala	102350	22200	61449	14855	6.89	1.49
Mendefera	28297	11095	42906	10477	2.70	1.06
Mai Mine	68264	25930	49861	11576	5.89	2.24
Dibaruwa	96472	26734	66967	15280	6.31	1.75
Zoba Maekel	**107907**	**53962**	**140967**	**31893**	**3.38**	**1.69**
Berik	27219	17631	32808	6609	4.12	2.67
Serejeka	27254	10138	43989	10456	2.61	0.97
Gala Nefhi	40414	23011	40754	8974	4.50	2.56
Asmara	13020	3182	23416	5854	2.22	0.54
Total	**1013171**	**240112**	**739299**	**181645**	**5.47**	**1.32**

Source: MOA, (2000a); MOA, (2000b).

[14] We use the terms agricultural land, cultivated land, and cropland interchangeably to refer to the total are of land allotted to farmers for cultivation. This includes both the land cultivated in the current period as well as land, which is left fallow for a year or two.

The topography, land use and population density vary considerably from one sub-zone to another. The proportion of total cultivated land as a percentage of total land varies from 10% in Adi Keih to 64% in Sub Zone Berik. The total area of land per household varies from 2.22 ha in Asmara Sub Zone to 10.96 ha in Mai Aini. The respective average total and agricultural lands are 6.05 and 1.24 in Zoba Debub and 3.38 and 1.69 in the Zoba Maekel.

5.3.2 The research villages

As discussed in section 5.2 we have taken three subregions in the Central Highlands each representing different biophysical and/or socio-economic situations – ZDE, ZDW and ZM. We have also selected three villages for an in-depth study representing the three subregions - Maiaha, Zibanuna, and Embaderho. In this section we will provide a brief description of the three villages.

Maiaha – This village is one of the 41 villages in the sub-zone of Segeneiti and it is located at 15^0 03’ North latitude and 39^0 06’ East longitude about 60 km southeast of Asmara. The total land area is 1037 ha of which 249.27 ha (24%) is currently cultivated. The rest is grazing land with scattered trees (bushes) mostly dominated by acacia. The topography of the land is highly rugged with most of the land not suitable for crop production (see Annex 1). The total number of households in the village is 190 of which 35 are female-headed. The average land and average cropland per household are 5.46 and 1.31 hectares respectively.

In terms of infrastructure, Maiaha is a typical village in the Central Highlands of the country with no access to electricity, current water, schools, health centres, grinding mills and postal and telecommunication services. There are neither dams nor wells in the village. People, therefore, fetch water from a stream at a five-to-ten minutes walking distance. Fetching water remains mostly women’s task. When ever available, donkeys are used to transport water; otherwise women use a 20-litre jerrican, which they carry on their back. Both humans and livestock use the stream. Shortage of water for drinking and other household uses is not a problem in the village. However, the fact that both livestock and humans use the stream, and that the same river is used for cleaning, may expose the people to water-related health problems. In addition, as the river is the only source of water throughout the year, livestock have to be trekked to the river at noon and back to the grazing lands which can sometimes be a long distance contributing negatively to their weight. Whether there is sufficient water that can allow irrigation in the village is not known yet. Recently, one person has started irrigating a small plot of land by pumping water from the stream.

Residents of the village have to travel to a health centre in Hadida – a village about 8 km south of Asmara - for health service. When people have more serious health problems, people are referred to a hospital in Segeneiti town, which is at a distance of 20 km from the village. Similarly, pupils from this village have to travel a long distance for schooling. There is not even an elementary school in the village so children have to travel more than six kilometres to Halibo Elementary School. There is no transport facility connecting Halibo and Maiaha villages. As children at early age cannot make a round trip of 12 kilometres every day, they are obliged to start schooling late. For junior high school education youngsters have to go to Hadida village and for a high-school they have to go to Segeneiti or Dekemhare towns, which are about 20 kilometres away. As making a round trip walking of 40 km per day is very difficult, students have often to depend on relatives living in those towns or organize themselves in groups and rent a room together, which involves expenses that only few can afford to incur.

A new all-weather gravel top road has been built after independence, which passes through Maiaha. As a result there is now a bus making a daily (some times two to three round) tour to Dekemhare – the major market centre in the region. However, due to the long waiting time and to spare transport fee many people still walk on foot to the market centre as well as to the neighbouring villages. The distance from the nearest paved (asphalted) road is about 10 kilometres.

Land is communally owned in Maiaha. There is a land committee, which is responsible for classifying the village land among different uses (cropland, grazing land etc.) and allocation of cropland to the households in the village. There are also sub-committees responsible for specific activities in the process of allocation of croplands. These sub-committees include the screening committee which is responsible for the identification of households eligible for a full or half share (*gibri*)[15], and the distributing committee which are responsible for classifying the total village cropland according to soil quality (taking soil type and slope into account). The land distributing committee divides the total agricultural land into blocks of land to be distributed to groups of households. For example, the total number of household in the village (about 200 households) is divided into 10 groups each group containing 20 households. The total cropland in the village is also divided into ten blocks – one for each group of household. Finally each group of households selects their own distributors to divide each block into equal units of land and makes it ready for final drawing of lots. This way each household gets its share of cropland in the village.

[15] As discussed in chapter two, all households with more than one member get the same size of land (full share or gibri) but households with only one member get only half of that size.

Maiaha, as most villages in the Central Highlands of Eritrea, has well established community rules and regulations for the use of woodlands and grazing lands. A watchman (known as *Nebera*) is appointed to see that the rules and regulations are respected. To allow regeneration of grasses, grazing lands are open for grazing in rotations in different periods of the year i.e. different parts of the grazing land are restricted and then opened for grazing in different months of the year. Some grazing land (known as *Hizaeti B'eray*), after being restricted for grazing for about eight months, is open for grazing exclusively for oxen, for some time before it is open to other types of livestock. Livestock are not allowed to graze around croplands during the growing season and livestock from neighbouring villages are not allowed to graze in the village territory. The *Nebera* (also known as *Zer'ay* in other parts of the Central Highlands) is responsible to see to it that all the above guidelines are respected. Trespassers, if found, are fined in kind (usually 2 to 4 kg of grain), which the watchman can keep for personal use. In addition, each farming household in the village pays in kind for the services of the watchman at the time of the harvest.

Maiaha has a relatively vast area of degraded woodland mainly dominated by acacia. In the past cutting of live trees was allowed with permission from village elders on occasions of wedding ceremonies, memorial of the dead, construction of houses for newly formed families and maintenance of the traditional houses called *Hidmo*[16]. Without such permissions, the cutting of live trees was forbidden but people can collect dry wood (or cut dead trees) for fuel. However, people who do not belong to the village were not allowed to cut trees or to collect dead wood in the village's territory. The watchman was expected to make a frequent tour of the woodlands and ensure that the rules were not breached.

After independence, the government, in its effort to control land degradation, has taken over the responsibility of managing the woodlands by appointing a watchman who is paid by the government. It is now illegal to cut live trees for whatever purpose. Trespassers are fined in cash and the regional office of the Department of Forestry and Wildlife in the Ministry of Agriculture collects the fine.

Zibanuna – This is a village located at 14^0 54' North latitude and 38^0 48' East longitude in the Mendefera sub-zone 63 km south of Asmara. Zibanuna is located in the most fertile areas of the Central Highlands of Eritrea where the topography is mostly flat and soils very deep. The total land area is 829.28 ha

[16] Hidmo is a typical traditional house in the Central Highlands where the walls are mostly built of stones but requires considerable amount of woods for the roof and the poles supporting it. This is often considered among the major factors causing deforestation in Eritrea (Atzbaha et al, 1998)

more than 40 % of which is currently cultivated. The area is almost entirely devoid of natural vegetation but plantations cover about 2.6 percent of the land. Grazing land covers for 8.65 percent of the total land area. The village has 278 households. Female-headed households constitute 33 % of the total households. The average land and average cropland in the village is 2.98 and 2.34 ha per household respectively.

In terms of infrastructure, the village being located close to Mendefera (the capital of Zoba Debub), is in a better position than most other villages in the study area. An asphalted road connecting Asmara and Adi Quala passes only half a kilometre from the village. The village has one elementary school, and the famous San Georgo high school of Mendefera is located on this village's land only two and half kilometres from the village. Similarly, although the village does not have its own health centre, grinding mills, telecommunication and postal services, etc. the residents of the village need only to travel less than 6 kilometres to get such services in Mendefera.

There is no current water in the village, but there are some wells and one dam and there is no acute shortage of water. An attempt to use the dam for irrigation purposes in the past caused the reservoir to dry before the arrival of the rainy season. Since then the water of the reservoir is exclusively used for drinking (humans and livestock) and other household uses, the wells are used for irrigation purposes. Those who engage in irrigation have to dig their own wells or to share the wells with others. Zibanuna is one of the villages were irrigation is relatively much practised in the Central Highlands of the country.

Three decades back land was privately (family) owned in Zibanuna. However with the coming to power of the socialist government of the Ethiopian Military regime in 1974, the communal land ownership system known as *diessa* was introduced. The way now land is distributed among members of the village in Zibanuna is similar to what we have discussed for Maiaha above.

Embaderho – This village is located at 15^0 23' North latitude, and 38^0 53' East longitude 12 km north of Asmara. The village is found in the Central Zone, Serejeka sub-zone. The topography is rugged with considerable part of the land marginally suitable for cultivation. The land is totally devoid of natural woodlands apart from 46 ha of eucalyptus plantations. The total cultivated land is about 1052 ha which is about 44 % of the total area (2404.69 ha). Embaderho is one of the largest villages in the Central Highlands of Eritrea with 1400 farming households. Female-headed households constitute about 30 percent of the households.

Embaderho has relatively better infrastructure compared to most villages in the Central Highlands. An asphalted road that connects Asmara and Keren passes through the village; a public transport as well as private busses passing through the village to Serejeka provides a relatively continuous transport service to the village. The village has been connected to electricity since mid 1980s. However, with the exception of few small businesses, electricity in this village is still used solely for lightening purposes. There are few small businesses in the village including groceries, bars and a small firm producing sand bricks.

Despite the fact that Embaderho is a large village with about 5600 inhabitants, it has only one elementary school and no junior or high school. Thus students have to travel to Beleza, a neighbouring village 6 kilometres away, for a junior high school and to Asmara for high school education. Other essential services such as health centre and a grinding mill are not available in the village.

Although there is no shortage of water in the village, there is no pipe water. There is one large reservoir, covering an area of 15.3 ha, and two small reservoirs covering a total area of 8.1 ha in the village. In addition, there is one stream and one well. The large dam is in a restricted area and is not used for any purpose. The two small dams are used as a source of drinking water for livestock and humans, other household uses as well as for irrigation. Irrigated farming is relatively a common practice in Embaderho mainly due to the relative abundance of water and the proximity of the village to the Asmara market. Shortage of motor pumps and shortage of labour are the major current constraints to irrigation in the village.

Land is communally owned and managed in Embaderho as in most parts of the Central Highlands. The Diesa system of land distribution is similar to what has been described above for Maiaha village.

5.4 Household resources

5.4.1 Labour

In the Central Highlands of Eritrea, where members of the household do almost all farming activities, the supply of labour for agricultural and other activities is determined by the size of the family and its composition. Men, women and children engage in most economic activities as weeding, harvesting, transporting crops and straw, tending and milking livestock, collecting fuel wood, marketing etc. However there are few activities that require particularly adult male labour such as ploughing and tending livestock when they migrate outside the village. There are also some activities that are traditionally women's tasks such as childcare and food preparation. Table 5.2 shows average family size and the age distribution of the population in the study area.

Table 5.2 Family size and household composition (2002)

	Sample size	Female-headed (%)	Family Size			Age groups (%)			
			Average	Min	Max	0-10	10-18	18-75	>75
ZDE	90	16	5.17	1	14	30	27	35	8
ZDW	90	21	5.98	1	12	28	30	40	2
ZM	90	12	6.27	1	13	29	28	39	4
Mean		16	5.74			29	28.3	38	4.7

Source: Own General Survey (2002)

The average family size is 5.74 ranging from 5.17 in ZDE to 6.27 in ZM. These figures are higher than the average family size in various regions of the Central Highlands, which ranges between 4 and 5 persons per household (FAO, 1994; KHC, 1996; MOA, 2000b). This is most probably a result of a lower proportion of female-headed households included in the sample. While female-headed households constitute 32 percent of all households in the survey villages, only 16 percent of the respondents were female-headed in our survey. The average family size for the female-headed households included in the general survey was 2.64. Similarly, a study by Kale Hiwet Church (1996) in four sub-zones in Zoba Debub shows that the average household size differs substantially between the male-headed households (5.9 members) and female-headed households (3.3 members). The major reason for the high proportion of female-headed households in the study area is the long war for independence and the recent border war, which costed the country tens of thousands lives.

The last four columns of Table 5.2 show the distribution of the population by age groups. The classification is made in such a way that it can help to determine the supply of labour for agricultural activities. The first and the last age groups, i.e. those below 10 years of age and those above 75 are considered to be economically non-active. This constitutes about 34 percent of the total population. The range of age for economically active population, 10 to 75, is based on the fact that children help with farming and other activities from early ages. This constitutes 66 percent of the population. Economically active adults, 18 to 75 years of age, constitute only 38 percent of the population.

Shortage of labour is a serious constraint both to crop as well as livestock production in the Central Highlands of Eritrea. The major cause shortage of labour is the thirty-year war of independence and the two year border conflict with Ethiopia that claimed tens of thousands of lives at the productive age group. This is reflected in the high proportion of female-headed households. The war has also made many more people to migrate. The shortage of labour is exacerbated by the large number of religious holidays observed by the followers of the Orthodox Church, the dominant church in the Central Highlands, during which no major agricultural activity could be undertaken.

Rural households in the study area practise various ways to overcome this problem. Collaboration between family members and close relatives is the most important one. Various forms of labour-labour, labour-oxen, oxen-straw and sharecropping arrangements are also practised. For example, a female-headed household with no adult male may depend on a close relative who would cultivate her land for free, spend some days weeding or harvesting the farm of another household who would supply adult male labour to cultivate her land in exchange, or she would rent the land and get a share of the harvest. The share of harvest may vary from half to one quarter depending on whether she is sharing the cost of production such as labour, seeds and fertilizer. The rural labour market in most parts of the Central Highlands is not well developed. Very few farmers (except those engaged in irrigated agricultural activities) employ paid labour even during the peak agricultural season. However, in villages close to the major urban centres, a large number of farmers are engaged in off-farm employment.

5.4.2 Land

Land is an important resource for rural livelihoods in the Central Highlands of Eritrea. Generally croplands are very small and fragmented. Both the size and quality of land vary considerably from one region to the other. Table 5.3 shows the average size of cropland households own, the number of plots, the average distance from home to the plots, the overall quality of the croplands, the need for soil conservation structures (terracing) and the extent to which such structures are already applied in ZDE, ZDW and ZM.

Table 5.3 Croplands in the Central Highlands, 2002

	Zoba Debub East	Zoba Debub East	Zoba Maekel
Average Farm Size (t*simdi** per household)	3.7	3.8	3.2
Average Number of Plots per household	3.5	4.4	3.3
Average Distance from the village (km)	1.8	1.5	2.5
Fertile Soil type (% of all plots)	50.0	56.0	57.0
Moderate to Steep Slope (% of all plots)	33.0	28.0	31.0
Need for Conservation (% of all plots)	84.0	56.0	71.0
Conserved Land (% of all plots)	57.0	35.0	53.0

* *Tsimdi* (literally pair) is a traditional measure of the size of cropland which is approximately 0.25 ha.
Source: Own General Survey (2002).

The average cropland in all the three regions (ZDE, ZDW and ZM) is less than one hectare per household. This is lower than the average cropland in the Central Highlands (about 1.32 ha per household) presented in table 5.1. As the size of land varies from one village to the other, the discrepancy can be due to small number of villages included in the General survey (only 9 villages were included in the survey out of a total of 967 villages in the Central Highlands). Another reason can be that *tsimdi* is a subjective measure. Defined as the area of land a pair of oxen can plough in a day, *tsimdi* can vary depending on the strength of the oxen, the type of land, the length of working time in a day etc. In the in-depth survey, all plots of croplands of ten farmers each in Maiaha, Zibanuna and Embaderho were measured. The average croplands in the three villages were 1.23, 1.04 and 0.48 ha per household respectively.

Land fragmentation is often considered as a problem in agricultural production in many developing countries. The arguments against land fragmentation are based on the wastage of time travelling from one plot to the next and the loss of agricultural land to crop production due to large number of borders between plots. Land fragmentation is common throughout the Central Highlands. This is because in the Diesa system of communal land ownership each farmer is allotted land in different locations to ensure equity. The average number of plots reported varies from 3.3 in Zoba Maekel to 4.43 in Zoba Debub. In fact, farmers may have more plots of croplands because they often report all plots in a single block as one[17].

The last four rows in table 5.3 refer to farmers' perceptions regarding the quality of their land, the extent to which croplands are exposed to erosion, the need for soil conservation and whether croplands have the necessary conservation structures or not. Of all the plots of cropland 50 to 60 percent were reported to be fertile. Although land is generally more fertile in ZDW, the farmers' classification does not show significant differences on the proportion of fertile and non-fertile plots in the three regions. This is probably because farmers classify a given plot of land as fertile or otherwise relative to the other plots in the same village.

While farmers believe that less than one third of their farms have moderate to steep slopes, they still believe that a large proportion of their croplands need soil conservation structures. More than half of the croplands in ZDE and ZM and more than one third of those in ZDW were reported to be terraced already.

[17] The way croplands in a village are first divided into blocks, which are then, further sub divided into individual farms is described in 5.3.2.

Table 5.4 shows farmers' soil fertility classification of croplands in the three study villages of Maiaha, Zibanuna and Embaderho. The farmers classified their farms into different categories of fertility based on the colour and texture of the soils. These categories include highly fertile soils (*Walakha*), moderately fertile (*Dukha, Shiebet* or *Sibuh*) and poor soils (*Tsebaria, Rekik*, or *Fequis*)[18].

Table 5.4 Soil quality on croplands in Maiaha, Zibanuna and Embaderho (%), 2002

	Maiaha	Zibanuna	Embaderho
Walakha (fertile)	-	48	-
Dukha (moderately fertile)	32	21	65
Tsebaria (poor soil)	68	31	35

Source: Own In-depth Survey (2002).

As shown in Table 5.4 Maiaha has the poorest soils with 68 percent of all plots included in the survey being classified as Tsebaria and none as Walakha. On the other hand Zibanuna has the most fertile soils with 48 percent of the soils classified as Walakha and 31 percent as Tsebaria. Sixty five percent of the soils were Dukha and the rest Tsebaria.

5.5 Crop production

The types of crops grown vary from one region to another mainly due to variations in altitude and soil type. Even in a given region and village the types of crops grown vary from one year to the other due to the practice of crop rotation as well as the onset of rains. Land that is planned to be used for finger millet (which has a long growing period) may be used for maize or sorghum if rains start later and for taff, barley or wheat if the rain starts even later in the rainy season. Cereal crops such as barley, wheat, sorghum and millet and pulses such as beans and chickpeas are the dominant crops in ZDE and ZM. In ZDW, on the other hand, cereals such as barley, sorghum and taff and pulses such as chickpeas and field peas are the major crops. In addition to these crops, which are mainly dependent on rainfall, a small scale of irrigated vegetables production is practised in some villages of the Central Highlands particularly in ZDW and ZM.

Although the choice of crops is dictated by factors such as altitude, soil type and the onset of rains, generally farmers in the Central Highlands choose to grow more than one crop at a given year. This is mainly a strategy of spreading risk as the susceptibility to drought and the outbreak of pests vary for different crops. In

[18] Walakha refers to the most fertile soils with dark brown colour and a clay loamy texture. Dukha, is the next fertile soil with lighter red brown colour and loamy texture and Tsebaria is the least fertile land with high percentage of coarse gravel (FAO, 1994).

areas where maize can grow and the rains start early enough, farmers prefer to have at least one plot cultivated with maize. This is because maize can be ready for consumption at the end of August when the household is in a serious shortage of food and the other crops are not yet ready for harvest. Farmers also prefer to produce some crops that have a relatively higher market value. Whenever climatic and soil conditions, such as soil quality and altitude are suitable taff is the most important crop in this respect. Pulses and finger millet, the best crop for the local beer called *Siwa*, also have a strong market demand and a relatively higher price compared to many rain-fed crops grown in the Central Highlands.

5.5.1 Crop yield

Crop yields vary considerably from one region to another and even within a given region due to variations in rainfall, soil quality, use of fertilizer and other land management techniques. Table 5.5 shows a summary of crop yield from the in-depth survey in the three villages of Maiaha, Zibanuna and Embaderho. Although differences in the types of crops grown in the three villages makes yield comparison difficult for all crops, A comparison of the yields of crops grown in the study villages shows that Embaderho has the highest yield. For example, the yield of barley in 2001 was 648, 1052 and 2294 kg/ha in Maiaha, Zibanuna and Embaderho respectively. The comparison of yields of wheat and potatoes in Zibanuna and Embaderho also shows similar results. Wheat and potatoes had a yield of 1271 and 7290 kg/ha respectively in Embaderho compared to 995 and 5529 kg/ha respectively in Zibanuna. This is surprising given the generally more fertile land of Zibanuna. The explanation is the higher rates of fertilizer use in Embaderho (see Section 5.5.3). The higher altitude of Embaderho, which results in a cooler temperature and hence lower evapotranspiration, also contributes to the relatively higher yields.

Table 5.5 Crop yield (kg/ha), 2001

Crops	Maiaha	Zibanuna	Embaderho
Sorghum	680.8	836.1	
Maize	1064.2		
Barley	649.3	1052.1	2294.2
Millet	501.0		
Beans	606.0		1562.2
Wheat		995.9	1271.3
Taff		786.0	
Chick pea		790.0	
Potatoes		5529.0	7290.7

Source: Own In-depth Survey (2002).

A number of studies show that basic food requirement was not met in Eritrea in the last three decades. Cliffe (1992) estimates that food production in a normal year covers only 55-60 percent of the annual food requirement in the country (see chapter two). Households in the survey were asked whether there is a change in crop yield and crop production in the last 20 years and what factors were responsible for such changes. To determine the changes in crop yield and production, respondents were asked what the crop yields (per *tsimdi*) were and for how many months the total production used to feed the family 20 years back. The same questions were also asked for the present time. Table 5.6 shows farmers' perception of the changes in crop yield and changes in the number of months covered by farmers' own production.

Table 5.6 Farmers' perception of changes in cereal production and productivity

	Crop yield (100 kg/*tsimdi*)			Months covered by own production		
	Past (20 year ago)	Present	% Change	Past (20 year ago)	Present	% Change
ZDE	6.8	2.5	-62.6	10.3	4.5	-56.6
ZDW	4.8	1.9	-60.8	10.8	4.5	-58.3
ZM	7.1	4.0	-43.1	9.7	5.9	-38.8
Mean	6.3	2.8	-56.1	10.3	4.9	-51.9

Source: Own General Survey (2002).

The total production of crops per household could change because of changes in yield as well as changes in farm size. As shown in table 5.6 farmers believe that crop yield in the Central Highlands has declined by on average 56.1 percent in the last two decades. The change in crop yield varies from 43.1 percent in ZM (from 7.1 to 4.0 quintals/ha) to 62.6 percent in ZDE (from 6.8 to 2.5 quintals/ha). Similarly the number of months covered by farmers' own production has declined by about 52 percent in the Central Highlands ranging from 38.8 percent in ZM to 58.3 percent in ZDW. It is important to note that farmers in this region have never been self-sufficient but the gap between food production and food requirement has been getting wider through time. Currently farmers on average can cover only about five months of their food requirements from their own production.

The results of the survey indicate that farmers believe that the major factor contributing to the decline in crop yield is shortage of rain (mentioned by 57 percent of all respondents) followed by shortage of labour (mentioned by 27 percent of the respondents). Declining land productivity due to soil erosion, reduced fallow and nutrient depletion is often cited as a cause of declining yields in the Central Highlands of Eritrea (see Chapter two). A significant number of the respondents referred directly or indirectly to a decline in land productivity as a cause for the declining yields. A decline in land productivity, lack of manure, soil erosion and reduced fallow together were mentioned by 28 percent of the

respondents. A decline in land productivity was a relatively important factor for yield decline in ZDE, where it was mentioned by 30 percent of the respondents, followed by ZM and ZDW where 28 and 22 percent of all respondents mentioned it respectively. This is understandable given the fact that ZDE has the most rugged topography and the least use of fertilizer to make up for the nutrients lost through soil erosion and nutrient depletion.
Another important observation from Table 5.7 is that a large number of (31 percent) respondents in ZM reported that there was no decline in crop yield during the last two decades. With this finding and the relatively higher yields (Table 5.6), it seems that farmers in this region have managed to reduce the decline in crop yields by relatively better management of their land such as a higher use of fertilizer and longer fallow period as reported from Embaderho (a village representing ZM).

Table 5.7 Reasons for yield decline over the past 20 years

Factor	ZDE		ZDW		ZM		Total	
	Freq.	%	Freq.	%	Freq.	%	Freq.	%
Shortage of rain	43	48	52	58	43	48	153	57
Shortage of labour	32	36	12	13	17	19	72	27
Decline in land productivity	8	9	5	5.5	6	6.7	24	9
Lack of manure	6	6.7	5	5.5	7	7.7	20	7
Erosion	5	5.5	5	5.5	1	1	11	4
Less fallowing	8	9	5	5.5	8	9	21	8
Other (lack of oxen, weeds, pests etc)	3	3.3	7	8.0	2	2	12	5
No decline	3	3.3	11	12	28	31	33	18

Source: Own General Survey (2002).

5.5.2 Labour and oxen requirement

Almost all crop production activities in the highlands of Eritrea are labour intensive, which are performed with the help of animal power and simple tools. The availability of labour and oxen determines the success of crop production because as the rainy season is very short in Eritrea the timeliness of the various farming activities and particularly sowing is critical. Since most of the farmers in the Central Highlands of Eritrea are followers of the Orthodox Church, they observe a number of days dedicated to the saints including Saturday and Sunday. No major farming activity such as ploughing, weeding, harvesting and threshing can be performed on these days. This considerably reduces the number of days farmers can work and thereby increasing the number of people and oxen required to do the jobs at the right time.

The average amount of labour required to cultivate one hectare of land is calculated based on the number of times each activity is done on every plot of cropland of the farmers included in the intensive survey and the amount of time that activity took. Table 5.8 shows labour requirement for the various farming activities. The frequencies of weeding and ploughing do not considerably differ in the three villages. The average number of times of ploughing (which includes land preparation and sowing) is approximately three. The number of ploughings required varies from one crop to the other. Generally taff requires a finer seed preparation and hence a larger number of times of ploughings. On the other hand, sorghum and pulses are reported to need the least number of ploughings.

The number of mandays required to do each farming activity per ha varies considerably from one village to the other. For example, Zibanuna has the lowest number of days needed to plough one hectare of land, probably because of the more fertile deeper soils. The lowest number of days to weed a hectare of land, on the other hand, was in Maiaha. This may probably be due to different level of weed infestation or the thoroughness of weeding done in the three villages. Finally, the mandays required for harvesting, threshing and transporting were the highest in Embaderho followed by Zibanuna. This is most probably due to the higher yields in those villages.

Table 5.8 Labour requirements for crop production

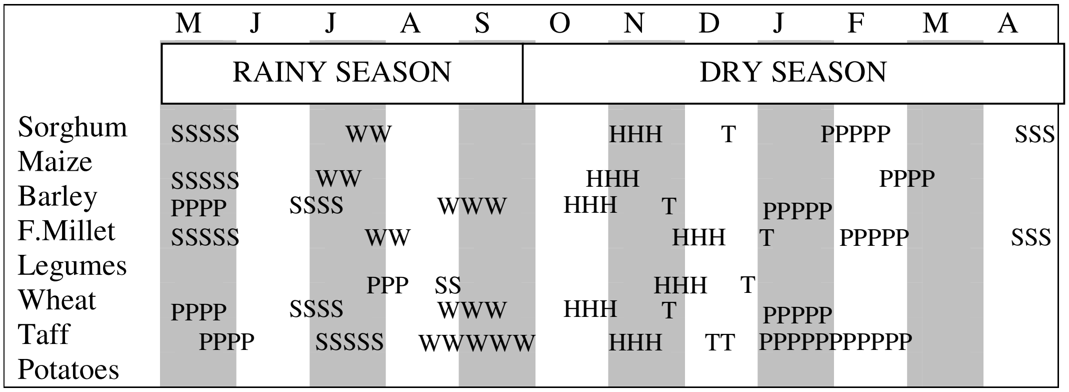
	Ploughing md/ha (a)	Av. No. ploughing (b)	Weeding md/ha (c)	Av. No weeding (d)	Harvesting md/ha (e)	Threshing & Transport md/ha (f)	Total* md/ha (g)
Maiaha	6.79	2.97	17.49	1.45	13.27	12.40	71.60
Zibanuna	3.55	3.20	32.85	1.42	29.93	16.95	104.89
Embaderho	6.91	2.79	34.86	1.13	30.13	31.99	120.79

g = (a*b) + (c*d) + e + f

Source: Own In-depth Survey (2002)

Both ploughing and threshing involve oxen power besides labour. For every manday of ploughing a pair of oxen is involved. The ratio between labour and oxen is not so definite for threshing as for ploughing, because for threshing three to five or even more oxen may be involved. But on average two people and about four oxen are involved in threshing and the ratio of two oxen for one person is a reasonable approximation for threshing as well. In addition to the amount of labour and oxen required to work one hectare of land, the length of period in which the job has to be done is also important to determine the extent to which the availability of these resources constrain crop production. While some activities such as land preparation can be done in an extended period of time (during the dry season), other activities such as sowing, weeding and harvesting have to be done in a relatively short period of time. The cropping calendar presented in Figure 5.1 shows the period in which different farming activities are undertaken in the Central Highlands of Eritrea.

Figure 5.1 Cropping calendar in the Central Highlands



S = sowing W = weeding H = harvesting T = threshing P = ploughing

5.5.3 Land management practices

Farmers in the Central Highlands of Eritrea practise various land management techniques to maintain and improve crop yield. These practices include fallowing, crop rotation, applying manure and chemical fertilizers as well as undertaking soil conservation activities. The extent and frequency of the above activities vary considerably from one region to another.

Fallowing

This practice is a widely used means of restoring land productivity in most parts of the highlands of Eritrea. In fact, when sufficient period of fallow is adopted this strategy also allows the regeneration of vegetation cover. Two methods of fallowing are practised in the Central Highlands of Eritrea. The first is a situation where land is left without any crop for one year. At the end of the rainy season in the fallow year (end of August or early September), the land is ploughed to increase water infiltration and to incorporate the grass as green manure. In the second case of fallowing, after staying idle for the most part of the rainy season, the land is used to grow chickpeas, which is believed to improve soil fertility. Although, due to the shortage of land the second type of fallowing is becoming common, farmers believe that the former one is more effective in restoring soil fertility.

When land is left fallow, it is used as grazing area for livestock. Thus, the decision whether and which parts of the croplands should remain fallow is made at a village level and not at the farm household level. In order to avoid the damage of crops by livestock, all croplands in a certain location are left fallow at the same year and once that location is declared fallow for the year, no farmer is allowed to cultivate his farm located in that area.

The frequency of fallowing and the number of years the land remains fallow vary from one village to another as well as between various croplands in the same village. In most villages land is cultivated two to three years before it is left fallow for one year. In many villages in ZDW, where land is relatively more fertile, fallowing is not practised at all. All croplands are cultivated continuously. In the other two regions, ZDE and ZM, fallowing is practised on most of the croplands except on the plots adjacent to the village (dwelling area) known as *Gedena*. These parts of the croplands are relatively more fertile because household waste and manure that are washed away from the village surroundings rest on them. In addition, if farmers have some manure, they first apply it on these plots because of their proximity to the village. When rains start early, *Gedena* is used to cultivate maize (and potatoes in some villages in ZM).

In only two of the nine villages included in the general survey longer fallow periods (up to six years) were used until recently. In fact, in one village (Awlie Tseru) in ZDE farmers complained that the Ministry of Agriculture prohibited them to cultivate their former cropland which they fallowed for six years. This is because the land is now covered with bushes and it is not allowed to cut trees.

In Embaderho croplands are cultivated for two to three years and then left fallow for the next two years. Farmers in Embaderho reported that they used to cultivate their land for three years before leaving it fallow for one year in the past but this has changed recently. The reason for leaving the land fallow for a second year, which was not observed in other villages, was shortage of grazing land. This is an interesting phenomenon because with higher population pressure it is expected that land is cultivated more frequently such that the length of the fallow period gets shorter and shorter. Asked if farmers noticed any change in the frequency and length of the fallow period, farmers in the remaining villages included in the general survey did not remember such change.

Crop Rotation

Crop rotation is another widely used practice in the highlands of Eritrea. All farmers in all villages and regions reported that they use crop rotation. However the type of crop cultivated is dictated very much by the onset of the rainy season as well as seed availability that farmers do not always stick to the sequence of crops. They often grow the same crop year after year. The major types of crop rotation in the three regions include:

ZDE	Barley – Sorghum or Finger Millet – Barley or Sorghum – Fallow
ZDW	Sorghum – Chickpeas or Taff – Barley and/or Wheat - Sorghum
ZM	Barley – Wheat or Beans – Fallow - Fallow

Crop rotation and fallowing practices are arranged in such a way that land redistribution will take place during the second fallow period. That is once farmers obtain a cropland they cultivate it for three years, leave it fallow for one year, and then cultivate it for the next three years. During the 8th year the land is left fallow again and land redistribution takes place during this year.

Intercropping is not a common practice in the Central Highlands of Eritrea except for barley and wheat.[19] The main reason for mixing the two crops is the better quality of bread the mixed crop makes than barley alone and the higher yield it gives than wheat alone. In fewer cases mixed cropping of Finger millet and sorghum is practised as well.

Fertilizers

Application of manure on croplands is one of the commonly used practices of restoring soil fertility in the Central Highlands of Eritrea. However, the amount of manure farmers apply on their croplands is very limited mainly due to the limited number of livestock they keep and the use of manure for fuel. Farm households often collect the manure, particularly from cattle, dropped on croplands and grazing areas for use as a fuel. Manure from cattle that is dropped at home at night is also dried and carefully stored for use as fuel in the dry season. In addition, farmers do not make serious effort to maintain the quality of manure by applying storage and utilization practices that would minimize nutrient losses and make the nutrients readily available to the plants. The manure is collected from the house compound (where livestock are usually kept overnight) and piled just outside the compound for months until they are taken to the field. This manure together with other household waste, ashes and leftovers of crop residues from livestock are transported to the field before the onset of the rainy season and ploughed into the soil.

The use of chemical fertilizers is very low in Eritrea. The average rate of chemical fertilizer applied was 20 kg per ha in 2001 (10,200 tons on 497,530 ha cultivated in 2001). This is very low even by Sub-Sahara African standards. Table 5.9 shows the type and extent of fertilizer use in the three study villages. The use of manure is generally low in all the villages but farmers in Zibanuna used even less manure with only 12 percent of all plots cultivated with the application of manure. This due to the fact that most of the land in this village is suitable for cultivation and hence, there is acute shortage of grazing land. As a result farmers in this village own smaller number of livestock (particularly sheep and goats) and therefore less manure is available. The application of chemical fertilizer, on the other hand, is relatively higher in Embaderho and Zibanuna.

[19] The mixed crop from barley and wheat is known as *Hanfets*.

The average amount of chemical fertilizer applied on fertilized plots in Embaderho and Zibanuna is 84 and 65 kg per ha respectively. The recommended rate of application of chemical fertilizer in the Central Highlands of Eritrea is 100 to 150 kg per ha (Barbier 2001). The use of chemical fertilizer is very low in Maiaha where it was applied only on 9 percent of all plots cultivated in 2001.

Table 5.9 The use of manure and chemical fertilizers

	Manure		Chemical Fertilizer		
	% of farmers	% of plots	% of farmers	% of plots	Average Qty applied Kg/ha
Embaderho	80	29	90	60	84
Maiaha	80	33	30	9	50
Zibanuna	40	12	100	58	65

Source: Own In-depth Survey (2002).

According to the farmers in the study areas the impact of manure and chemical fertilizers on crop yield is not very different. Farmers believe that the application of fertilizer (organic or inorganic) could increase yields by 125 to 150 percent. However, farmers said that manure is preferred to chemical fertilizer because while chemical fertilizer needs to be applied every year, manure once applied serves for two to three years. They also emphasized that the application of chemical fertilizer results in a higher yield only when there is sufficient rain.

In addition to manure and chemical fertilizer the use of municipal waste as fertilizer was reported in Embaderho. In this village, while chemical fertilizer is applied to most plots, manure and municipal wastes are particularly applied to the irrigated fields. The application of manure in all the study villages is done by donkey and camel loads and sometimes by renting trucks.

Soil Conservation Practices

Most of the soil conservation structures established with food-for-work programs is done on non-cropland hillsides. However, there exist some well-developed terraces on moderate to steep slope croplands that have been developed through time. It is common in many villages to find almost flat croplands in areas that have generally moderate slopes. This shows that farmers were very much aware of the erosion problem and used to take measures to prevent soil loss and conserve moisture. This is supported by a study in the Central Highlands of Eritrea that showed that about 70 percent of a total 300 respondents believed that their croplands suffer from moderate to high rates of soil erosion (Araya 1997). The same study also shows that more than 70 percent of the farmers believe that erosion considerably reduces yield. However, it has been observed in the field study that croplands with very steep slopes have been cultivated without any physical soil conservation structures in ZDE and ZM.

Farmers in the study area generally believe that most of their croplands need some conservation measures. Table 5.10 summarizes farmers' perception on which of plots need soil conservation structure and which of the plots already have sufficient conservation structure in ZDE, ZDW and ZM.

Table 5.10 Farmers' perception on the need and extent of terracing on own croplands

	Plots that need soil conservation (%)	Plots that already have sufficient conservation structure (%)
ZDE	84	57
ZDW	56	35
ZM	71	53

Source: Own General Survey (2002).

Households in the survey have been questioned about the major constraints to undertake activities that improve lands productivity such as the use of fallowing, crop rotation, the application of manure and chemical fertilizers and terracing. Shortage of labour was the major constraint for the application of soil conservation structures and, next to the availability of manure, the second most important factor that hinders the application of manure. Lack of finance was the most important constraint to the application of chemical fertilizers. But lack of finance as a constraint for the application of chemical fertilizer is more pronounced in ZDE where it was mentioned by 62% percent of the respondents than in region two or three where only 38 and 18 percent respectively mentioned it as a constraint.

5.6 Livestock

Livestock production is very important to rural income and food security in Eritrea. The main species found in the study area are cattle, donkeys, sheep, goats and poultry. Farmers also keep some bees. Oxen and donkeys are important sources of draught power and transport. The other types of livestock are important sources of milk and meat for household consumption, as a source of cash, as well as security and investment. Another highly valuable animal product is dung, which is used as fuel and fertilizer.

Most farmers keep oxen and donkeys because of their importance in crop production and other activities. Table 5.11 shows that only 29.6 and 28.8 percent of the respondents owned no ox and no donkey respectively compared to 74.6 and 75.3 percent who did not own any cow or no sheep/goat respectively. This shows that when households, due to financial, labour or feed constraints, can not keep more livestock, they prefer to keep working animals such as oxen and donkeys to other types of livestock.

Table 5.11 Ownership of Livestock in the Central Highlands, 2002

	Percentage of households who own		
	Zero	One	Two or more
Oxen	29.6	27.2	43.2
Donkeys	28.8	61.7	9.5
Cows	74.6	14.9	10.5
Sheep/goat	75.3	1.0	23.7

Source: Own General Survey (2002).

Both the composition and number of livestock are slightly different in ZDW compared to the other two regions. As this region has flat topography and fertile soils most of the land is used for crop cultivation. This means there is less grazing land and therefore lower number of livestock. The average number of tropical livestock unit for all regions is 2.18 ranging from 2.0 in ZDW to 2.3 in ZM. While ZDW has less of all types of livestock, the difference is more pronounced in the case of sheep and goat (Table 5.12).

Table 5.12 Ownership of livestock in the Central Highlands, by region 2002

	Oxen/ hh	Cow/hh	Donkey/ hh	Sheep/ Goat/hh	TLU/hh	Percentage of households with		
						No oxen	One oxen	Two or more
ZDE	1.25	0.46	0.72	2.68	2.20	30.0	31.1	38.9
ZDW	1.17	0.41	0.78	1.86	2.00	36.4	19.3	44.3
ZM	1.23	0.46	0.98	2.54	2.30	25.6	32.2	42.2
Mean	1.22	0.45	0.82	2.39	2.18	30.6	27.6	41.8

Source: Own General Survey (2002).

Table 5.13 shows the number of livestock in Maiaha, Zibanuna and Embaderho. As shown in the last column of the table, the existing number of livestock far exceeds the carrying capacity of the villages. The gap between the carrying capacity and the existing livestock is the largest in Embaderho followed by Maiaha and Zibanuna respectively. This clearly shows that shortage of animal feed is the most serious constraint for livestock production in the study villages.

The communal grazing land and crop residues are the major sources of animal feed in the study villages. Livestock are taken together to the communal grazing areas during the day and return to the homestead during the night where they are fed straw, which has been conserved after the harvest. The arable lands become an important grazing area for two to three months after harvest. The most difficult period is the end of the dry season, just before the arrival of the rains. Farmers try to keep enough straw for this period. Animal feed in most cases must be supplemented by straw of barley wheat and taff for the months between March and August.

Table 5.13 Number of livestock and carrying capacity in Maiaha, Zibanuna and Embaderho, 2002

	Number of livestock				TLU	Carrying Capacity* TLU/village	TLU/carrying capacity
	Ox	Cow	Donkey	Sheep /goat			
Maiaha	300	405	100	500	683	170	4.02
Zibanuna	168	99	122	46	303	126	2.40
Embaderho	2500	400	800	2000	3380	385	8.78

* Carrying capacity is determined at 6 ha per TLU
Source: Respective village administration, (FAO, 1997).

Migration of livestock is a common strategy of alleviating feed shortage practised in most villages in the Central Highlands of Eritrea. Cattle are the main types of livestock that move from one place to another in different seasons although sheep and goats also sometimes move with the cattle. Livestock from Maiaha and Embaderho migrate to Semienawi Bahri[20] from December to June and to Barka and Gash basins in the western lowlands from July to August. The duration of the migration varies from one village to another and from one household to another household. But in some villages in ZM (including Embaderho) all livestock except oxen are required to migrate at least for one month (August). Households whose cattle migrate may either send one or more of the household members with the livestock[21] or find someone who would keep their livestock in return for the milk and manure from the cattle (if there are sufficient milking cows) or in return for a cash payment. Seasonal migration of livestock is not practised in Zibanuna. Farmers in Zibanuna supplement the shortage of animal feed by purchasing crop residues from the neighbouring villages. Even in ZDE and ZM the migration of livestock is declining due to shortage of labour and because most of children in rural areas these days are going to school. Despite the fact that households in all villages supplement the shortages of animal feed by migration or purchase of feed, there is acute shortage of feed in the Central Highlands of Eritrea so that animals are often underfed. This is reflected in the slower growth and lower weight of livestock.

Shortage of labour is another major constraint for livestock production in the region. Farmers in the study area deal with the problem of shortage of labour by keeping their livestock together. Mostly farmers form groups (consisting of

[20] Some times referred to just Bahri, Semienawi Bahri is a part of the green belt zone in the eastern escarpment that enjoys two seasons of rainfall in a year.
[21] When households migrate with their livestock to Semienawi Bahri, they do not only tend their livestock but also grow crops on own or rented land.

varying members depending on the number of livestock) and tend their livestock in rotations, where the number of days a household is responsible is proportional to their livestock. Alternatively farmers hire a village herder to care for their animals in a communal system, which costs them between three and four Nakfa per head per month. In addition, the households provide the meal of the herder in rotations.

5.7 Tree planting

As discussed in Chapter two, the vegetative cover in the highlands of Eritrea is highly degraded with most areas almost devoid of the natural vegetation. However, some acacia woodlands and bush lands still remain in many parts of the highlands. The three regions included in our study vary considerably in terms of land cover. ZDE has relatively better natural vegetation cover compared to ZDW and ZM. The possible reason for less natural vegetation in ZDW is, most likely, the use of land for annual crop production. This is because owing to the flat topography and fertile soils almost all the land in this region is favourable for crop production. On the other hand, the lower vegetative cover in ZM is the result of a higher population density and its proximity to the capital city. Information about the area under natural vegetation and the extent of vegetation cover for the various regions was not available.

Plantations of eucalyptus have been practised in the highlands of Eritrea for a long time. Most of the plantations have been done in the ZM (see chapter two). Communal as well as individual plantations exist both in Zibanuna and Embaderho villages. However there are no community plantations in Maiaha and individual trees are insignificant.

Table 5.14 Eucalyptus plantations in the study villages, 2002.

	Area under plantation (ha)	Average number of trees per HH	Maximum number of trees	Minimum number of trees	Farmers with no trees (%)
Maiaha	0.0	1.4	6	0	60
Zibanuna	21.5	15.6	50	0	20
Embaderho	46.9	26.0	70	0	40

Source: Own In-depth Survey (2002).

Table 5.14 shows the area under eucalyptus plantations and the number of trees farmers own in the three study villages. The area under eucalyptus plantations (communal and individual) in Zibanuna and Embaderho villages is 21.5 and 46.9 hectares respectively. This is about 2.6 and 1.9 percent of the total area of the two villages respectively. Similarly the number of households with no trees in the study villages constituted 60%, 20% and 40% percent of the total respondents in Maiaha, Zibanuna and Embaderho respectively.

The use of trees for construction purposes was the most commonly cited reason for planting trees in all regions followed by fuelwood. Other objectives mentioned often by households who plant small numbers of trees were, shade and memorial for the martyrs of the war for liberation. The major reason for not planting trees given by households in all regions is lack of land which is a result of the communal system of land ownership (see Chapter three). Other constraints mentioned include, lack of labour, lack of fencing material, and poor survival rate of trees (mostly due to pests).

5.8 Summary

An extensive field study was undertaken to understand the farming systems in the Central Highlands of Eritrea, to explore farmers' perceptions on the major constraints to their farming activities and to obtain some parameters to the mathematical model described in the previous chapter. The results show that the regions in the Central Highlands vary considerably both in terms of resource endowments, as well as the extent of use of external inputs and other modern agricultural practices. The regions also vary with respect to access to additional grazing land in the eastern escarpments and access to markets (proximity to major towns) and development of infrastructure. In all regions shortage of male labour resulting from the war of independence and mobilization of labour for the recent border war has considerably affected agricultural activities.

The major parameters obtained from the fieldwork include the size and composition of labour, land and livestock resources, labour and oxen requirement for various farming activities and the timing of those activities. Farmers' perceptions of the impact of soil erosion and the application of manure and fertilizer application on crop yield were also explored. The results generally show that farmers are aware of the problems of land degradation and believe that most of their croplands need stone bunds and fertilization. Farmers emphasize that shortage of rainfall is the major bottleneck to crop production and the most important reason for the low levels of application of chemical fertilizers. Shortage of labour is the major reason mentioned by most farmers for the low levels of soil conservation. The communal land tenure system is also a serious constraint to tree planting and soil conservation activities in the Central Highlands of Eritrea.

Chapter 6

Bio-economic Model of the Farming Systems in the Highlands of Eritrea

6.1 Introduction

In Chapter four, we have presented the major biophysical and socio-economic components of the mathematical model that will be used to analyse farmers' decisions in the Central Highlands of Eritrea. We have described current and potential economic activities and technologies as well as interactions among the various economic activities and biophysical components of the farming system. The socio-economic activities include crop production, livestock production, and tree planting and off-farm employment. The major resources of the farm households include labour and land. The biophysical processes included in our model are soil erosion and nutrient balance (particularly nitrogen). The use of organic and chemical fertilizers, the application of soil conservation structures (stone bund), and tree planting (planting eucalyptus and allowing natural regeneration of woodlands) are the major technologies under consideration.

6.2 Mathematical modelling of the farming systems

Farmers make a large number of decisions. A distinction can be made between decisions on production, consumption and trade and decisions on the application of soil conservation techniques. Production decisions and decisions aimed at improving the natural resource base are often interdependent. The most part of what farmers consume is often produced at the farm and therefore farmers' production decisions are influenced by their consumption habit or vice versa in that activities related to one can have a positive or negative impact on the other. For example, a decision to apply manure on cropland to increase crop production will also improve the soil quality. On the other hand a decision to cultivate steep-slope to increase production, leads to higher erosion.

As farmers make a large number of decisions, we will concentrate on the main decisions about the allocation of their limited resources (mainly land and labour) on crop production, raising livestock and tree planting. Towards this end we will identify the relevant production, consumption and trade decisions. A decision variable refers to a variable whose optimal level must be determined. A parameter refers to an exogenous factor. A state variable is determined by the values of already defined decision variable(s) and parameter(s).

Once the relevant decisions are identified, we will discuss which exogenous factors affect the decision and the parameters involved. We will adopt a certain rule of notation: all decision variables and state variables will be written in capital letters, and the exogenous factors or parameters by a small letter. The relevant production, consumption and trade decisions, the factors that affect the decisions as well as the relationship among them will be described and modelled in the following sections.

6.3 The planning year and the planning period

As the mathematical model we develop incorporates activities and investments with long-term returns such as tree planting and the construction of soil conservation structures, we will develop a dynamic (multi-annual) model. Thus we will define a planning period as the period (number of years) during which the benefits of all activities and investments will be fully utilized. The number of years in the planning period is called n. We number the years of the planning period as 1, 2, …n and define the set T:

$$T = \{1, 2, \ldots, n\} \quad (1)$$

Farming activity in general and crop production in particular is a seasonal activity. As the farming system in the highlands of Eritrea is generally characterized by rain-fed crop production, both rural income and labour demand for agricultural activities have seasonal characteristics. Most of the jobs have to be done between June and November, which is a peak season in agricultural activities and crops are harvested between October and December. In addition, the availability of labour varies accordingly as many farmers who have off-farm jobs may return to their farming activities and young family members are available full time for farming activities as schools are closed.

We, therefore, define a planning year, which consists of the twelve months following the beginning of the first of January. As the availability of labour as well as labour requirement for farm activities vary considerably from time to time we will divide each planning year into 18 different periods of two weeks or one month. We will divide the six months starting the beginning of June through the end of November (peak period for agricultural activities) into periods of two weeks and the rest 6 months in periods of one month. Thus we will have a set P:

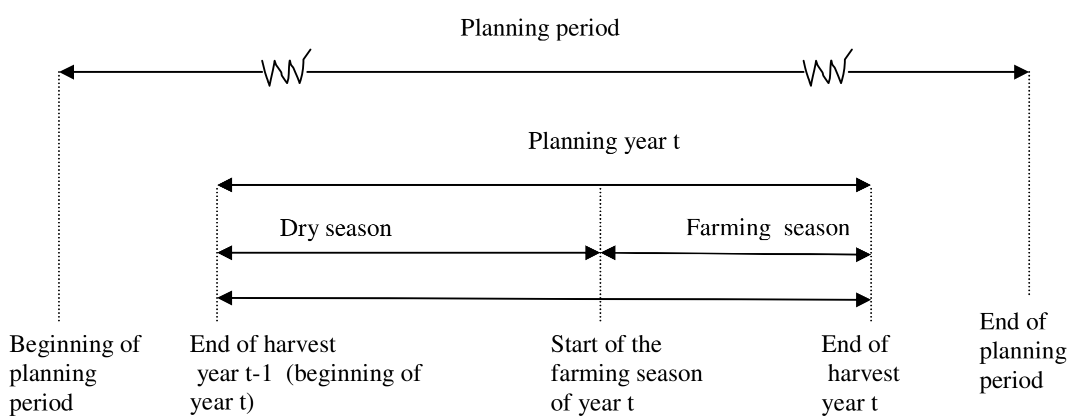
$$P = \{p_1, p_2, \ldots p_{18}) \qquad (2)$$

Where:

p_1:	the month of January	p_{10}:	the first half of August
p_2:	the month of February	p_{11}:	the second half of August
p_3:	the month of March	p_{12}:	the first half of September
p_4:	the month of April	p_{13}:	the second half of September
p_5:	the month of May	p_{14}:	the first half of October
p_6:	the first half of June	p_{15}:	the second half of October (3)
p_7:	the second half of June	p_{16}:	the first half of November
p_8:	the first half of July	p_{17}:	the second half of November
p_9:	the second half of July	p_{18}:	the month of December

A schematic presentation of the planning period and planning year is given in figure 6.1

Figure 6.1 Planning period and planning year



6.4 Land use decisions and land constraints

Each village in the highlands of Eritrea has a limited land area with different slope and soil quality categories. Soil depth, nutrient contents and soil erosion vary across fields of different soil types. As a result, while some soil types are cultivated continuously, others have to be left fallow after cultivating two or three years. A detailed classification of land with respect to slope, soil depth and organic matter content is not available for the study area. As the rate of soil erosion is very much related with slope of land, we will use only the later as a basis for classifying various categories of land. We distinguish four different soil types called s_1, s_2, s_3, and s_4 with:

$s_{1:}$ a slope of 0-8 percent
$s_{2:}$ a slope of 8-16 percent
$s_{3:}$ a slope of 16-30 percent (4)
$s_{4:}$ a slope of 30 percent or more

We will refer to these as “categories of land”, “soil types” or “type of land”. The set of these four types of land will be defined as:

$$S = \{s_1, s_2, s_3, s_4\} \tag{5}$$

The decisions faced by farmers with respect to land use include:

- Fields to be cultivated and fields to be used for grass and tree planting
- The types of crops to be cultivated on each soil type
- Types and doses of fertilizer to be applied on the different soil types
- The type of soil conservation structure to be built on the different soil
- types

In connection with these decisions, we define four sets relating to types of crops, types of fertilizer, types of soil conservation structures and types of trees. The major types of crops that grow in the study villages include barley, wheat, maize, sorghum, beans, millet, and taff. For reasons of convenience grass and fallow are defined as crops as well. Let us first define a set C as the set that consists of nine types of crops:

$$C = \{c_1, c_2, c_3, c_4, c_5, c_{6,} c_7\}, \tag{6}$$

where

c_1 = barley c_6 = fallow (7)
c_2 = millet c_7 = grass
c_3 = beans
c_4 = sorghum
c_5 = wheat (taff)

Manure, crop residues and chemical fertilizers (Urea and DAP[22]) can be applied as fertilizers. Crop residues may also be left on the farm as mulch to improve soil structure. Each fertilizer can be applied in different rates (kg/ha) on its own or in combination with another fertilizer (see also Section 6.7 in this chapter). We will define a set F that consists of seven types of fertilizers.

[22] Urea contains 46% of Nitrogen by weight and DAP (Diammonium Phosphate) contains 18% of Nitrogen and 46% of phosphorus by weight.

$$F = \{f_0, f_1, f_2, f_3, f_4, f_5, f_6\} \,, \tag{8}$$

where

f_0 = no fertilizer
f_1 = 1800 kg of manure (9)
f_2 = 3600 kg of manure
f_3 = mulch and manure (500kg of crop residues + 500 kg of Manure)
f_4 = mulch and chemical fertilizer (500kg of crop residues + 50 kg of Urea + 50 kg DAP)
f_5 = 50 kg of Urea + 50 kg DAP
f_6 = 100 kg of Urea + 50 kg DAP

We also define the set W as a set that consists of two types of soil conservation structures.

$$W = \{w_0, w_1\}, \tag{10}$$

where

w_0 = no conservation structure (11)
w_1 = stone bund

We finally define a set Y as a set that consists of two types of woodlands (see Chapter four)

$$Y = \{y_1, y_2\}, \tag{12}$$

where

y_1 = natural woodlands dominated by acacia trees (13)
y_2 = plantations dominated by eucalyptus trees

In the definitions to be introduced below, land of soil type s with soil conservation structure w, is simply called 'land of type (s,w)'. Similarly, crop c is often used in combination with fertilizer f. We will, therefore, simply talk about 'crop (c,f)'. If in a certain year t on a plot of land of soil type s stone bunds are constructed, then the plot is of type (s,w_0) at the beginning of the year and of type (s,w_1) at the end of the year. By definition, 'land type (s,w)' in year t refers to the situation at the end of the year.

As villages in the highlands of Eritrea have clear boundaries, the total area of land available for the various activities (cropland, grassland and woodland) as well as the current allocation of land among those activities is given. For $s \in S$, $w \in W$, $y \in Y$, we introduce the following parameters:

cland0(s,w)	area of cropland of soil type (s,w) at the beginning of the planning period, in ha	(14)
tland0(s,w,y)	area of treeland of soil type (s,w) under tree y at the beginning of the planning period, in ha	

At the village level decisions will be made on the allocation of the available land for different uses. Land may be used for crop production, tree planting or grazing. In our base model we assume that fertilizer can be applied only on croplands but soil conservation structures can be built on croplands, woodlands, as well as grasslands. We introduce two types of time indices t and tt, which will help us to remember the age of the trees and to calculate the age dependent wood production. For all $s \in S$, $w \in W$, $c \in C$, $f \in F$, $y \in Y$, $t \in T$ and tt = 0, 1, 2 .. t, we define the following decision variables:

CLAND(s,w,c,f,t)	area of land of soil type (s,w) where in year t crop (c,f) is cultivated, in ha.	(15)
TLAND(s,w,y,tt,t)	area of land of soil type (s,w) where in year t trees of species y grow which were planted in year tt, in ha.	(16)

Special attention deserves TLAND(s,w,y,0,t) which refers to the area of land of soil type (s,w) where in year t trees of species y grow, which were planted before the planning period. From definition (16) also follows that, for all tt = 1, 2, … t :

TLAND(s,w,y,tt,tt)	area of land of soil type (s,w) where in year tt trees of species y are planted, in ha.	(17)

The establishment of soil conservation structures reduces the area of land that can be used for crop production or tree planting. The length of conservation structures required to control soil erosion from different land categories is different because the extent of erosion varies with the slope of the land. The area that will be occupied by the conservation structures also varies proportionally. Thus we define the following parameter:

pstone(s)	proportion of land type (s) occupied by stone bunds	(18)

If stone bunds are constructed on a piece of land of size a, the area of (1-pstone(s)) $\times$ a can be used for crop or tree planting. We will assume that stone bunds can be constructed on woodlands only if the trees are first cleared. The land may then be replanted or used for crop production. We introduce the following decision variables for all s ∈ S, p ∈ P, t ∈ T:

TSTONE(s,p,t) area of land of soil type s, where in year t-1 trees grow, which are cut in year t, and where stone bunds are constructed in period p of year t, in ha (19)

CSTONE(s,p,t) area of land of soil type s, where in year t-1 crops are grown and in period p of year t stone bunds are constructed, in ha.

Farmers may also decide to cut trees and use the land either to cultivate crops or replant it with trees. We define for all s ∈ S, w ∈ W, y ∈ Y, t ∈ T and tt = 0,1,2 ..t-1:

TCLAND(s,w,y,tt,p,t) area of land of soil type (s,w), where in period p of year t trees of species y, which were planted in year tt, are cut, in ha (20)

Stone bunds can be constructed only on land that had no stone bunds previously. Thus we have the following conditions for s ∈ S, t ∈ T, t ≠ 1, and tt = 1, 2, …t:

$$\sum_{p} CSTONE(s,p,t) \le \sum_{c,f} CLAND(s,w_0,c,f,t-1) \tag{21}$$

$$TSTONE(s,p,t) \le \sum_{y,tt} TCLAND(s,w_0,y,tt,p,t) \tag{22}$$

Equations (21) and (22) also apply if the right hand sides are replaced by

$cland0(s,w_0)$ and $\sum_{y} TCLAND(s,w_0,y,0,p,1)$ respectively. (23)

Note that for reasons of convenience we adopt the notation $\sum_{c,f}$ to refer to summation over all elements of c ∈ C and f ∈ F. Similarly, $\sum_{y}$ and $\sum_{p}$ refer to summations over all elements of y ∈ Y and p ∈ P respectively.

6.4.1 Tree growth and the land constraints

The repartition of the available land into crop and woodland, with and without stone bunds, in year t can be different from the repartition in year t-1, because of the following possible activities in year t:

- construction of stone bunds

- cutting of trees
- planting of trees

If trees are cut, woodland is converted into croplands or trees are replanted. If trees are planted, cropland is converted into woodland or woodland is replanted with trees. These possible activities show up in the following expressions, which represent the interrelations between planting, growth and cutting of trees in various years of the planning period. We call these expressions the *tree-balance equations*. For all $s \in S$, $w \in W$, $y \in Y$, $t \in T$ but $t \neq 1$, and tt = 0,1,2… t-1, it may be written:

$$TLAND(s,w,y,tt,t) = TLAND(s,w,y,tt,t-1) - \sum_{p} TCLAND(s,w,y,tt,p,t) \quad (24)$$

For t = 1 we have:

$$TLAND(s,w,y,0,1) = tland0(s,w,y) - \sum_{p} TCLAND(s,w,y,0,p,t) \quad (25)$$

All variables introduced so far are supposed to be non-negative. It follows from (24) therefore, that for all $s \in S$, $w \in W$, $y \in Y$, $t \in T$, and tt = 0,1,2… t-1, it has to be satisfied:

$$0 \leq \sum_{p} TCLAND(s,w,y,tt,p,t) \leq TLAND(s,w,y,tt,t-1)$$

Of course no more trees can be cut in year t than there are available.

The variables defined in (15) and (17) are decision variables determining the planting of crops and new trees in year t. For all $s \in S$, $t \in T$, the expression

$$\sum_{y,p} TLAND(s,w_1,y,t,t) + \sum_{c,f} CLAND(s,w_1,c,f,t)$$

represents the total area of land type (s,w_1) where in year t crops are cultivated and new trees are planted. The available land for these crops and for new trees consists of the following parts:

a) the crop land of type (s,w_1) in year t-1:

$$\sum_{c,f} CLAND(s,w_1,c,f,t-1)$$

b) the crop land of type (s,w_0) in year t-1, where in year t stone bunds are constructed:

$$(1 - pstone(s)) \times \sum_{p} CSTONE(s,p,t)$$

c) the woodland of type (s,w_0) in year t-1, where in year t trees are cut and stone bunds are constructed

$$(1 - pstone(s)) \times \sum_{p} TSTONE(s,p,t)$$

d) the woodland type (s,w_1) in year t-1, where in year t trees are cut:

$$\sum_{y,p} \sum_{tt=0}^{t-1} TCLAND(s,w_1,y,tt,p,t)$$

Thus for all $s \in S$, $t \in T$, $t \neq 1$, and for $w = w_1$, it may be written:

$$\begin{aligned}\sum_{y} TLAND(s,w_1,y,t,t) + \sum_{c,f} CLAND(s,w_1,c,f,t) = {} & \sum_{c,f} CLAND(s,w_1,c,f,t-1) \\ & + (1 - pstone(s)) \times \sum_{p} \{CSTONE(s,p,t) + TSTONE(s,p,t)\} \\ & + \sum_{y,p} \sum_{tt=0}^{t-1} TCLAND(s,w_1,y,tt,p,t)\end{aligned} \tag{26}$$

Equation (26) holds also for t = 1, if $\sum_{c,f} CLAND(s,w_1,c,f,t-1)$ is replaced by $cland0(s,w_1)$. (27)

Similarly for $w = w_0$ and $t \in T$, and $t \neq 1$:

$$\begin{aligned}\sum_{y} TLAND(s,w_0,y,t,t) + \sum_{c,f} CLAND(s,w_0,c,f,t) = {} & \sum_{c,f} \mathrm{CLAND}(s,w_0,c,f,t-1) \\ & - \sum_{p} \{CSTONE(s,p,t) + TSTONE(s,p,t)\} \\ & + \sum_{y,p} \sum_{tt=0}^{t-1} TCLAND(s,w_0,y,tt,p,t)\end{aligned} \tag{28}$$

Equation (28) holds also for t=1 if $\sum_{c,f} CLAND(s,w_0,c,f,t-1)$ is replaced by *cland0(s,w_0)*. (29)

Note that in (26) and (27) the losses of available land due to the construction of stone bunds are taken into account by including the parameter (*1-pstone(s)*). Understandably, the parameter is not included in (28) and (29).

The expressions (24) – (29) represent the *land constraints*, which postulate that in each year and for each land type (s,w), the land in use for crop and tree cultivation equals the available land. The equality says that all the village land will be used for one or the other type of economic activity at any given time.

This is because grass and fallow land, which require little labour input, are included. The total land area of type s available at the village remains the same throughout the planning period. The area where stone bunds have been constructed, however, changes over time.

Moreover, additional constraints will be imposed that reflect the suitability of different soil types for crop production. For example soil type s_4 is too steep to be used for crop production. Thus we have the following constraints:

$$CLAND(s,w,c,f,t) = 0 \text{ where } s = s_4 \text{ for all } c \in C, c \neq c_7; f \in F, w \in W \text{ and } t \in T \tag{30}$$

6.5 Crop production and consumption modelling

Crop production at any given time is a function of yields and crop area. Yield, in turn, is a function of various factors including soil type, the type and quantity of fertilizer applied, as well as the application of soil conservation methods (see Chapter seven). For all $s \in S$, $w \in W$, $c \in C$, $f \in F$, $t \in T$, we define the following parameter.

yld(s,w,c,f) yield of crop (c,f) from soil type (s,w) in year t (31)

Fallowing is a common practice in the Central Highlands of Eritrea (see Chapter five). We will assume that if a certain plot is cultivated at any time, some other parcel of land will remain fallow at the same time. We call this parcel the fallow supplement of the cultivated crop. We will assume that the length and frequency of fallowing (and hence the size of the fallow supplement) does not depend on the type of soil, or the application of fertilizer. Thus we define

fal the ratio of area of land left fallow in year t to the area of land cultivated in year t (32)

If fallow land corresponds to crop (c_6, f_0), the total fallow land type (s,w) in year t is given as follows:

$$CLAND(s,w,c_6,f_0,t) = \sum_{c,f} fal \times CLAND(s,w,c,f,t) \tag{33}$$

No fertilizer is applied on fallow and grassland. Thus:

$$CLAND(s,w,c,f,t) = 0, \text{ for } c = c_6, c_7; f \in F, f \neq f_0 \tag{34}$$

The total production of each crop, in any given year will be the yield per hectare of that crop multiplied by the area of land occupied by that crop under the various land management practices. We define for all $c \in C$, $t \in T$:

TPROD(c,t) total amount of crop c produced in year t, in kg (35)

The crop production of crop $c \in C$ in year t is given by:

$$TPROD(c,t) = \sum_{s,w,f} yld(s,w,c,f,t) \times CLAND(s,w,c,f,t) \tag{36}$$

6.5.1 Crop residues

Crop production results into the production of an important by-product – crop residues. Crop residue is an important supplement as animal feed in the Central Highlands where shortage of animal feed is the major constraint to livestock production. Crop residues, particularly residues of maize and sorghum are also used as fuel. Another possible use of crop residues which is not currently practised in the study area is as fertilizer (see chapter five). We will assume that the amount of crop residues produced is proportional to crop production, i.e., the ratio between crop yield and a crop residue does not depend on the type of fertilizer applied or the construction of stone bunds. However the ratios of crop residue to crop yield vary from one crop to the other. Thus we define the following parameter and state variable for all $c \in C$, $t \in T$:

CROPRES(c,t)	total amount of crop residues of crop c produced in year t, in kg	
resid(c)	the ratio of crop residues to yield of crop c	(37)

The total amount of crop residue from each crop is given as follows:

$$CROPRES(c,t) = resid(c) \times TPROD(c,t) \tag{38}$$

Crop residues produced in a given year may be used in the same year or stored for use in the following years. Thus the sum of crop residues used for the various uses in a given year should not exceed the crop residues of each crop produced in that year plus residues carried over from the previous year, which implies the conditions in (40) and (41). We first define the following variables and a parameter for $c \in C$ and $t \in T$:

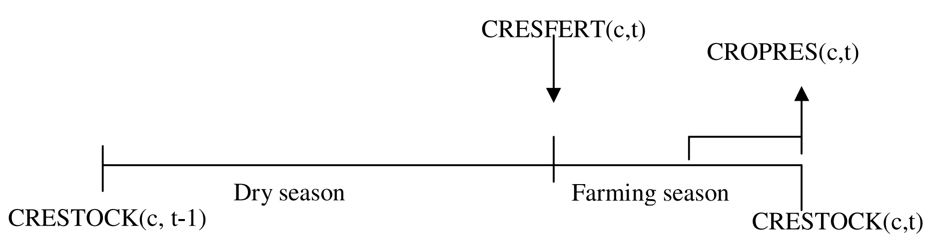
CRESFUEL(c,t)	the portion of residues of crop c used as fuel in year t, in kg	(39)
CRESFEED(c,t)	the portion of residues of crop c used as animal feed in year t, in kg	
CRESFERT(c,t)	the portion of residues of crop c used as fertilizer in year t, in kg	
CRESTOCK(c,t)	the amount of residues from crop c that remain in stock at the end of year t, in kg	
crestock0(c)	the amount of residues from crop c available in stock at the beginning of the planning period, in kg	

The *stock equations* for the residues for $c \in C$ and $t > 1$ and $t = 1$ are given in (40) and (41) respectively.

$$CRESTOCK(c,t) = CRESTOCK(c,t\text{-}1) + CROPRES(c,t) - CRESFUEL(c,t) - CRESFEED(c,t) - CRESFERT(c,t) \quad (40)$$

Equation (40) also applies for t=1 if *CRESTOCK(c,t-1)* is replaced by *crestock0(c)* (41)

Figure 6.2 Periods when crop residues are produced and applied for mulching



As shown in the above diagram, if crop residue is applied as fertilizer (mulching) in year t, it has to be applied at the beginning of the farming season, in which case crop residue to be used for mulching in a given year has to come from crop residues produced in previous year. Thus for all $c \in C$ and $t \in T$ and $t \neq 1$, the following condition must be satisfied.

$$CRESFERT(c,t) \leq CRESTOCK(c,t-1) \quad (42)$$

Condition (42) also applies to t=1 if *CRESTOCK(c,t-1)* is replaced by *crestock0(c)* (43)

6.5.2 Consumption, buying and selling of crops

The household can do a number of things with its production. It may consume part of its produce, keep part of the produce to be used as seed, sell it in the market and/or store it for use in the coming year. The household may also buy crops from the market or use a stock of crops from previous years. Price variations in different periods of the year and farmers' buying and selling strategies in different periods within one year are not taken into consideration. However, due to the fact that farmers usually sell crops right after the harvest when prices are lower and buy in later periods when price are higher, the buying and selling prices of each crop will be different. For c $\in$ C and t $\in$ T we define the following variables and parameters.

BUYCROP(c,t)	the amount of crop c bought during year t, in kg	(44)
SELLCROP(c,t)	the amount of crop c sold during year t, in kg	
FOOD(c,t)	amount of crop c consumed by the village members during year t, in kg	
SEED(c,t)	amount of crop c used as seed in year t, in kg	
STOCK(c,t)	stock of crop c at the end of year t, in kg	
popl(t)	total number of people in the village in year t	
calcont(c)	amount of calorie in one kilogram of crop c, kilocalories	
calreq	annual amount of calorie requirement per person, in kilocalories	
sdreq(c)	seed requirement of crop c, in kg/ha	
popl0	total number of persons in the village at the beginning of the planning period	
stock0(c)	amount of crop c available in stock at the beginning of the planning period	

The minimum calories required for all residents of the village have to be met from the crops consumed by the members of the village. Thus for all t $\in$ T:

$$\sum_{c=1}^{5} calcont(c) \times FOOD(c,t) \geq calreq \times popl(t) \tag{45}$$

The amount of seed of crop c required in each year is proportional to the area of land cultivated with that crop in the same year. For all c $\in$ C and t $\in$ T we write:

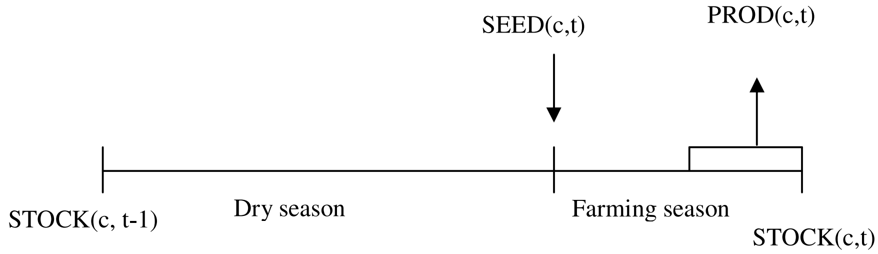
$$SEED(c,t) = \sum_{s,f,w} sdreq(c) \times CLAND(c,s,f,w,t) \tag{46}$$

We also write the *crop balance equations* for c $\in$ C and t$\in$T, t $\neq$ 1 as follows:

$$\begin{aligned} STOCK(c,t) = STOCK(c,t-1) + PROD(c,t) + BUYCROP(c,t) \\ - SELLCROP(c,t) - FOOD(c,t) - SEED(c,t) \end{aligned} \tag{47}$$

To write the crop balance equation for t = 1, the first term in (47) will be replaced by stock0(c), i.e., the stock of crop c at the beginning of the planning year. (48)

Figure 6.3 Crop production and seed requirement



The diagram in Figure 6.3 shows that while the production of crops is harvested at the end of the farming season, seed is required at the beginning of the farming season. Equation (49) ensures that the seed required in each year must be met from what remains in stock from previous year and/or from crop bought in the year in question.

$$SEED(c,t) \leq STOCK(c,t-1) + BUYCROP(c,t) \qquad (49)$$

Condition (49) also applies to t=1 if *STOCK(c,t-1)* is replaced by *stock0(c)* (50)

We also postulate *STOCK(c,t)* ≥ 0 for all $t \in T$ (51)

This implies that there is enough crop to cover food demand and seed requirement in each year. We will later make modifications to reflect the situation where rural households face shortages.

6.6 Wood and grass production

As discussed in Chapter three rural households in the highlands of Eritrea widely use tree products mainly for fuel wood and construction. These resources may be obtained from natural woodlands or from individual or community plantations. Thus farmers will have to decide on the area of land they want to keep under natural woodlands and under plantations. The decision will be influenced by the opportunity cost of the land (forgone crop production or grazing) and the costs involved in establishing and maintaining plantations on the one hand and the benefits in terms of output of tree products on the other. The production of wood for various uses in year t will be expressed in the variables already introduced. We define for all $s \in S$, $w \in W$, $y \in y$, $t \in T$, tt = 0,1,2…t:

WDHARV(s,w,y,t)	harvested wood in year t from trees of species y growing on land type (s,w), in kg	(52)
vwtland(s,w,y,tt,t)	volume of wood in year t of all trees of species y, which were planted in year tt and have grown all years tt, tt+1,…t on the land of type (s,w), in kg/ha	
wdyld(s,w,y)	annual increase in the volume of wood from tree species y planted on land type (s,w), in (kg/ha/year)	
vwtland0(s,w,y)	initial volume of wood on woodlands of tree species y, in kg/ha	
VWDWDL(y,t)	total amount of wood type y in woodlands in year t	

Initially there is a stock of wood in the woodlands. The stock of wood will decrease when rural people collect wood for fuel and other uses and when woodlands are converted into crop or grasslands. On the other hand, the stock of wood will increase over time by the establishment of new woodlands and the natural growth on the woodlands. For the purpose of simplicity we will express the volume of wood on a per hectare basis. We will also assume that if farmers collect wood, they cut all the trees on a piece of land[23]. Moreover, although the rate of growth of trees is of a non-linear nature where yield (the mean annual increment) depends on the age of the trees, due to lack of data we will assume a linear growth. The yield of wood varies by the type of trees planted as well as by the type of land. For $s \in S$, $w \in W$, $y \in y$, $t \in T$, tt = 1,2…,t, the parameters in (52) can approximately be written as:

$$vwtland(s,w,y,tt,t) = wdyld(s,w,y) \times (t - tt) \tag{53}$$

For tt = 0 we have:

$$vwtland(s,w,y,tt,t) = vwtland0(s,w,y) + wdyld(s,w,y) \times (t - tt) \tag{54}$$

Note that the parameter *vwtland(s,w,y,tt,t)* is expressed on a per ha basis and changes over time only due to natural growth. The initial values *vwtland0(s,w,y)* are estimated on the basis of the age of the trees. Also note the wording "have grown all years tt, tt+1,…,t on the land type (s,w)" in the definition of *vwtland(s,w,y,tt,t)* in (52). If trees grow in year t on land without stone bunds, then they have grown on land without stone bunds throughout all years tt, tt+1,…, t. Thus for $s \in S$, $w \in W$, $y \in y$, $t \in T$, tt = 0,1,2…,t, the amount of wood harvested may be written as:

[23] In practice farmers may collect dry wood or cut only branches of a tree as well.

$$WDHARV(s,w,y,t)=\sum_{tt=0}^{t}\left\{vwtland(s,w,y,tt,t)\times\sum_{p}TCLAND(s,w,y,tt,p,t)\right\} \quad (55)$$

The total amount of wood that is available on the woodlands, for y ∈ y, t ∈ T, will then be written as follows:

$$VWDWDL(y,t)=\sum_{s,w,tt} vwtland(s,w,y,tt,t)\times TLAND(s,w,y,tt,t) \quad (56)$$

The wood farmers harvest can be used as fuel, but there is also the possibility of selling it either for fuel wood or for construction purposes in the case of eucalyptus. Only some portion of the eucalyptus can be used for construction purposes (say 20%). Rural households may also buy fuel wood. Thus we introduce the following three non-negative decision variables:

WDFUEL(y,t)	amount of wood type y that is used as fuel in year t, in kg	
SELLWOOD(y,t)	amount of wood type y sold in year t, in year t in kg	(57)
BUYWOOD(y,t)	amount of wood type y bought in year t, in kg	
WDSTSOCK(y,t)	stock of wood from tree species y at the end of year t, in kg	
wdstock0(y)	initial stock of wood type y available for use, in kg	

This leads, for all s ∈ S, w ∈ W, y ∈ y, t ∈ T, t ≠ 1, to the following constraints:

$$\begin{aligned}WDSTOCK(y,t)&=WDSTOCK(y,t-1)+\sum_{s,w}WDHARV(s,w,y,t)\\&+BUYWOOD(y,t)-SELLWOOD(y,t)-WDFUEL(y,t)\end{aligned} \quad (58)$$

Equation (58) also applies to t = 1 if the first term in the right hand side of the equation is replaced by *wdstock0(y).* (59)

Equations (58) and (59) show that households can use wood harvested or bought in previous years if it is not used or sold in that year.

6.6.1 Grass production

Grass is produced from grasslands, fallowlands and woodlands. We assume that the yield of grass from grasslands and fallowlands are the same. The yield of grass from woodlands, however, differs due to differences in tree density which, in turn, differs by types of trees[24]. The total amount of animal feed available to the farmer is the sum of grass from all the above sources. So we introduce the following parameters and state variables.

gryld(s,w)	yield of grass from grassland of land type (s,w)	
gryldw(s,w,y)	yield of grass from woodland of land type (s,w) where tree type y is planted, kg/ha	(60)
GRASS(t)	total amount of grass produced in year t, in kg	

The total grass production in year t, for all s ∈ S, w ∈ W, y ∈ y, t ∈ T, tt = 0,1,2…,t, is written as follows:

$$GRASS(t) = \sum_{s,w} gryld(s,w) \times \{CLAND(s,w,c_6,f_0,t) + CLAND(s,w,c_7,f_0,t)\} + \sum_{s,w,y,tt} gryldw(s,w,y) \times TLAND(s,w,y,tt,t)) \tag{61}$$

6.7 Livestock modelling

The growth of the livestock is determined by weight gain and birth and mortality rates. Households decide the number and composition of livestock they keep in each period. They also buy and sell livestock if it is economically attractive. The common types of animals they keep include oxen, cows, donkeys, sheep and goat. Different animals are kept for different purposes. Thus we will distinguish between four types of livestock where

v_1: oxen
v_2: cows (62)
v_3: donkeys
v_4: sheep and goats

and define the set V which consists of four types of livestock.

$V = \{v_1,v_2,v_3,v_4\}$ (63)

In deciding on the number of livestock they keep, farmers compare the benefits and costs of keeping additional livestock. Benefits include milk from cattle, sheep and goats; cash from selling livestock; and animal power for traction and transport by oxen and donkeys respectively. The costs, on the other hand, include cash outlays for veterinary services and reduced income from other

[24] Leaves from natural woodlands are important source of animal feed in the Central Highlands. See chapter seven on estimations of yield of grass from natural woodlands and eucalyptus plantations.

activities (such as crop production) as raising livestock competes for limited resources such as labour and land.

The number of livestock in any given year is determined by the number of livestock at the beginning of the year, the natural rate of growth, as well as the buying and selling decisions of the farmers (see Section 7.6 how the natural rate of growth of livestock is determined). We introduce the following variables and parameters:

LVSTK(v,t)	the number of livestock units v in the village at the end of year t	(64)
SELVSTK(v,t)	the number of livestock units of type v sold during year t	
BUYLVSTK(v,t)	the number of livestock units of type v bought during year t	
lvstck0(v)	the number of livestock units of type v available in the village at the beginning of the planning period	
grlvstk(v)	annual natural rate of increase in the number of livestock v	

Thus for all v ∈ V and t ∈ T, t ≠ 1, the number of livestock v in year t will be:

$$LVSTK(v,t) = (1 + grlvstk(v)) \times [LVSTK(v,t-1) + BUYLVSTK(v,t) - SELLVSTK(v,t)] \tag{65}$$

Equation (65) also applies to t = 1 if $LVSTCK(v,t-1)$ is replaced by $lvstck0(v)$ (66)

6.7.1 Feed availability and livestock

We assume that some minimum number (proportional to the cropland cultivated) of oxen and donkeys will be required for ploughing and transport purposes respectively. The maximum number of livestock farmers can keep is also determined by the availability of fodder i.e. the upper limit of this choice will be determined when the village decides to allocate land among crop production, grazing and tree-planting activities. This is because such a decision determines the amount of forage available for livestock.

We have already defined *CRESFEED(c,t)*, (39) which indicates the proportion of crop residue to be used as animal feed. We have also defined *GRASS(t)* the amount of animal feed available from grasslands, woodlands and croplands (60).

We introduce the parameters in (67) which indicate feed required for each type of livestock, dry organic matter content of grass and crop residues respectively.

feedreq(v)	amount of feed required per unit of livestock type v, in kg DOM/year	
domcong	Dry Organic Matter content of grass, in kg/kg of grass	(67)
domconcr	Dry Organic Matter content of crop residue, in kg/kg of crop residue	

For t ∈ T, we impose the following constraint:

$$\sum_{v} feedreq(v) \times LVSTK(v,t) \leq \sum_{c} domconcr \times CRESFEED(c,t) + domcong \times GRASS(t) \tag{68}$$

i. e the total animal feed requirement must be satisfied by all the resources used as animal feed. We will later include the possibility of purchasing animal feed.

6.7.2 Animal power requirement and livestock

The minimum livestock units required for ploughing, transporting crops, crop residues, manure etc. to and from the farm, home and market, determines the lower limit of the number of livestock kept by farmers. Almost all ploughing is done by animal traction using a pair of oxen. Therefore, the amount of area cultivated for crop production is limited by the availability of oxen (v_1). The availability of iron plough and other farm implements is considered less a constraint and therefore not considered here. The number of days an ox is available for work is limited by religious reasons and physical capacity of the ox. The amount of area cultivated in any given year will also be limited by the amount of adult male labour that has to accompany the pair of oxen. As some agricultural activities have to be done in a given period (sometimes of very short duration) that it is necessary to impose constraints regarding animal labour requirement on a period by period basis (see the cropping calendar in fig 5.1). We define the following parameters for all c ∈ C, p ∈ P:

oxcult(p,c)	number of oxen days required in period p per ha of land category s, used to cultivate crop c.	
oxdays(p)	number of days an ox can work in period p	(69)

For t ∈ T and p ∈ P we write the constraint:

$$\sum_{c,s,f,w} oxcult(p,c) \times CLAND(c,s,f,w,t) \leq oxdays(p) \times LIVESTOCK(v_1,t) \qquad (70)$$

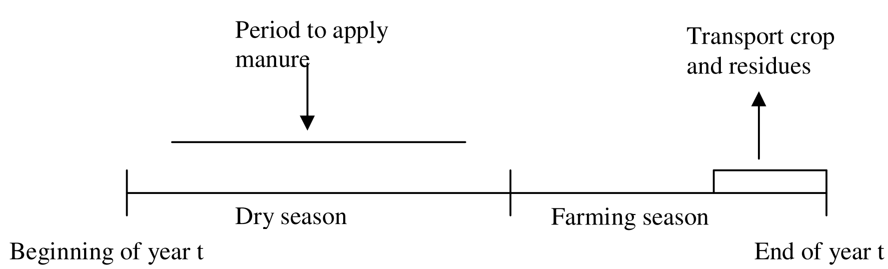
Donkeys (v_4) serve a number of activities including transporting crops and crop residues from the farm to the house, transporting manure to the field, fuel collection, fetching water and transporting goods to and from the market. However, donkeys are more intensively used in periods when agricultural activities are at peak. We will, therefore, impose a constraint relating only to those periods. The transportation capacity is determined by the number of donkeys, the number of days a donkey can be used in a given period and the average ton/km capacity of a donkey. For $p \in P$ we introduce the following parameters:

donkday(p) number of days a donkey can work in period p (71)

wdonkey weight potentially transported by a donkey, in ton km/day
distf average distance of cropland from the village (settlement), in km

As discussed in Chapter five, livestock are allowed to graze on croplands after the harvest. Thus farmers have to collect their crops and crop residues as soon as possible. Thus the transportation of crops and crop residues has to be carried out in a specific period. Similarly, the application of Manure has to be done before the onset of the farming season so that the manure would be mixed with the soil during land preparation. Figure 6.4 shows the periods during which the application of manure and transportation of crops and crop residues should be made.

Figure 6.4 Periods where animal power is required for transport of manure, crop and crop residues



Thus we include additional constraints as in (72) and (73). The constraints show that the total number of animal days required to transport crops, crop residues and fertilizer between the farm and the house in each period should be less or equal to the transportation capacity of the livestock. For $t \in T$ we write the constraints:

$$\sum_{p=12}^{18} LIVSTCK(v_3,t) \times donkday(p) \times wdonkey \geq \sum_c CROPRES(c,t) \times distf + \sum_c PROD(c,t) \times wdonkey \tag{72}$$

$$\sum_{p=2}^{6} LIVSTCK(v_3,t) \times donkday(p) \times wdonkey \geq MANFERT(v,t) \times distf \tag{73}$$

6.7.3 Milk production

The average milk production multiplied by the total number of livestock gives the total volume of milk production. For all v ∈ V and t ∈ T we define the following variable and parameter (74) and write an equation for milk production as shown in (75):

MILK(t) Total milk production in year t in litres
myld(v) the average yield of milk per head livestock v in litres/year (74)

$$\sum_v myld(v) \times LVSTK(v,t) = MILK(t) \tag{75}$$

6.7.4 Manure production and use

Manure is another important resource produced by livestock. In the Central Highlands of Eritrea where farmers are too poor to afford chemical fertilizer, manure is the major type of fertilizer applied to maintain soil fertility. Manure, particularly from cattle, is also an important source of fuel for domestic energy. Both the quantity of manure produced from each type of livestock and the nutrient content of the manure depend on the quantity and type of animal feed. We, nevertheless, assume that livestock are fed a certain fixed quantity (according to feed requirement for each type of animal) and produce the same quantity and quality of manure. We also assume that the nutrient content of manure is the same. We introduce the following variables, parameters and an equation for manure production for v ∈ V and t ∈ T.

MANURE(v,t) total amount of manure produced by livestock type v in year t, in kg (76)
manyld(v) average amount of manure per animal produced by livestock type v, in kg/year

$$MANURE(v,t) = manyld(v) \times LVSTK(v,t) \tag{77}$$

The total amount of manure will be used either for fuel or fertilizer. Manure produced in a given year may be used in the same year or stored for use in the following years. We thus define two non-negative decision variables, a state variable and a parameter for $v \in V$ and $t \in T$ as follows: and write the manure constraint as follows:

MANFERT(v,t) quantity of manure from livestock v used as fertilizer, in kg
MANFUEL(v,t) quantity of manure from livestock v used as fuel, in kg (78)
MANSTOCK(v,t) amount of manure from livestock v available in year t, in kg
manstock0(v) mount of manure available in the village at the beginning of the planning period, in kg

Thus the *manure balance* for $v \in V$, t =1 and t > 1 respectively are written as:

$$\begin{aligned} MANSTOCK(v,t) = {} & MANSTOCK(v,t-1) + MANURE(v,t) \\ & - MANFERT(v,t) - MANFUEL(v,t) \end{aligned} \tag{79}$$

Equation (79) also applies to t=1 if $MANSTOCK(v,t-1)$ is replaced by *manstock0(v)* (80)

Livestock produces manure throughout the year. However manure produced during the farming season is not available for use as fertilizer in the same year. Assuming that only half of the manure produced in a given year could be applied as fertilizer in that same year, we need the following additional constraints. For $v \in V$, t > 1 and t =1 respectively:

$$MANFERT(v,t) = MANSTOCK(v,t-1) + 0.5 * MANURE(v,t) \tag{81}$$

Equation (81) also applies to t=1 if $MANSTOCK(v,t-1)$ is replaced by *manstock0(v)* (82)

6.8 Fertilizer balance

Farmers can use fertilizer produced on the farm (manure and crop residues) and/or buy chemical fertilizer. The amount of crop residues and manure available for use as fertilizer is influenced by decisions of the farmers relating to crop and livestock production as well as his decision on how to allocate these resources among different uses such as fertilizer, fuel and animal feed. The amount of input used as fertilizer should not exceed the amount of that input available for use as fertilizer. We assume that farmers will use each type of fertilizer either at a prescribed rate or do not use that input at all. For $f \in F$, we define the following parameters:

manurate(f)	amount of manure applied when fertilizer type f is applied, in kg/ha	(83)
residrate(f)	amount of crop residue applied when fertilizer type f is applied, in kg/ha	
urearate(f)	amount of Urea applied when fertilizer type f is applied, in kg/ha	
daprate(f)	amount of DAP applied when fertilizer type f is applied, in kg/ha	

Note that for all $f \in F$ the values of these parameters are given due to the definitions in (9).

The available fertilizer is composed of four components, two of which, *CRESFERT(c,t)* and *MANFERT(v,t)*, already described as the portion of crop residues and manure respectively used as fertilizer in (39) and (76). The remaining two, Urea and DAP, refer to chemical fertilizers and we introduce two related decision variables indicating the amount of each type of chemical fertilizer bought and used in each year. We first define the decision variables for $t \in T$:

BUYUREA(t)	amount of Urea purchased in year t, kg	(84)
BUYDAP(t)	amount of DAP purchased in year t, kg	

To ensure that the demand for each type of fertilizer does not exceed the supply, for $t \in T$, we include the following constraints:

$$\begin{aligned}
&\sum_{v} MANFERT(v,t) = \sum_{s,w,c,f} manurate(f) \times CLAND(s,w,c,f,t) \\
&\sum_{c} CRESFERT(c,t) = \sum_{s,w,c,f} residrate(f) \times CLAND(s,w,c,f,t) \\
&BUYUREA(t) = \sum_{s,w,c,f} urearate(f) \times CLAND(s,w,c,f,t) \\
&BUYDAP(t) = \sum_{s,w,c,f} daprate(f) \times CLAND(s,w,c,f,t)
\end{aligned} \tag{85}$$

6.9 Energy modelling

Rural households use fuel wood, dung, crop residues and kerosene for cooking, heating and lightening purposes. Using kerosene and purchasing wood from the market involve cash outlays. Alternatively, farmers may obtain biomass resources freely from natural sources but this involves opportunity costs in terms of labour for their collection as well as forgone output from alternative use of the resources. Thus the costs and benefits associated with each source of energy determine the composition of fuels for households use. We define a decision variable and some parameters as follows:

KEROSENE(t)	amount of kerosene bought in year t, in litres	(86)
crencont(c)	the amount of useful energy per unit of residues from crop c, in MJ/kg	
mnencont(v)	the amount of useful energy per unit of manure from livestock v, in MJ/kg	
wdencont(y)	the amount of useful energy per unit of wood from tree of species y, in MJ/kg	
krencont	the amount of useful energy per unit of kerosene, in MJ/litre	
enreq	average energy requirement per person per year, in MJ	

The total amount of energy households' use from all those resources should at least be equal to the minimum energy requirements of the population. For $v \in V$, $c \in C$, $y \in Y$, and $t \in T$, we have the following constraint:

$$\begin{aligned} enreq * popl(t) \leq & \sum_c crencont(c) \times CRESFUEL(c,t) \\ & + \sum_v \; mnencont \times MANFUEL(v,t) \\ & + \sum_y \; wdencont(y) \times WDFUEL(y,t) \\ & + krencont \times KEROSENE(t) \end{aligned} \tag{87}$$

We will later consider other options related to rural energy such as new energy saving stoves and the use of liquefied petroleum gas (LPG).

6.10 Population and labour

As discussed in 6.3 both the demand for and the supply of labour in the rural areas vary considerably from one period to the other. Thus it is important that we put the labour constraint for each period. In addition, we will also distinguish between adult male labour and total labour available for agricultural activities.

This distinction is necessary because while most farming activities can be done by any member of the household, ploughing (land preparation and sowing) is traditionally done by men. Due to the 30 years war of independence and the recent war with Ethiopia, shortage of adult male labour is a serious constraint in agricultural production in Eritrea (see Chapter five).

The number of days each labour category is available for various economic activities is an important constraint for the farming household. In this study we will assume that this is a parameter. We will calculate the number of days members of a household (adult male, adult female and children) will be available for agricultural activities by taking into account all relevant variables. For example children will be available only for part of the days when schools are open; women's time will be adjusted for the time required to undertake household responsibilities and both adult male and adult female time will be adjusted for other social obligations. Finally the number of days rural household can undertake agricultural activities in each period is limited by religious holidays. However such constraints do not apply to non-farm activities. Thus we distinguish between number of days in which any activity can be done and number of days in which only some activities can be done in each period. Population size in any given year is the population in the previous year adjusted for the natural rate of growth. Migration into and out of the village is not considered in this study. For $p \in P$, and $t \in T$, we define some parameters.

avmlbag(p,t)	the quantity of male labour (days) available for agricultural activities in period p of year t	(88)
avmlbal(p,t)	the quantity of male labour (days) available for all activities in period p of year t	
avlbag(p,t)	the total amount of labour (days) available for agricultural activities in period p of year t	
avlbal(p,t)	the total amount of labour (days) available for agricultural activities in period p of year t	

Along with land, labour, is the most important input in the rural areas of Eritrea for all economic activities. Crop production, livestock and tree planting all require labour. The amount of labour required to cultivate a hectare of cropland depends on the land management practices of the farmer. The application of fertilizer and soil conservation activity influences the amount of labour input required in crop production. Application of manure and crop residues as a fertilizer requires labour (and/or animal power) to transport them to the fields. The constructions of soil conservation structures also require considerable amount of labour. The amount of labour required for transporting fertilizer varies with distance to the farm. For simplicity we will consider the average distance of the farms from the village. The amount of labour required for undertaking conservation activity and the area occupied by the conservation structures, on the other hand, vary with land categories. Farms on steep slopes require longer structures because conservation structures have to be built close to each other on steeper farms than on farms with gentle slope. Thus the amount of labour required for undertaking conservation activities varies with the slope of the land.

In addition, labour is required to keep livestock. The amount of labour required to take care of livestock is very difficult to model precisely, mainly because of the various types of arrangements made amongst households in the villages of the Central Highlands (see Chapter five and Chapter seven).

Labour is also required to plant trees. The amount of labour required for this activity is available from the records of the Ministry of Agriculture (see Chapter seven). Finally labour is required for the collection of fuel wood and dung. However, discussions with farmers show that households collect fuel wood and dung either in periods when they are free from agricultural activities or on their way home after accomplishing their agricultural task. Therefore, we do not include labour required for fuel collection in our labour constraint in (90). The benefits from tree planting will be included in the model not from the time saved in fuel collection but from the manure and crop residue that can eventually be used as fertilizer and animal feed respectively (rather than using them for fuel) and the potential to sell fuel wood and/or construction materials.

Farmers in the Highlands of Eritrea, particularly those in villages close to the capital city and major towns, are also involved in off-farm employments. The availability of off-farm employment opportunity was difficult to determine from the fieldwork as most of the young people are mobilized to join the army (see Chapter five). We assume only adult males will have access to off-farm jobs. We define a decision variable and parameters as follows:

OFFARM(p,t)	the number of days farmers in the village engage in off-farm jobs, in mandays/year	
labcult(c,p)	amount of labour required in period p to cultivate one ha of land under crop c excluding labour required for the construction and maintenance of stone bunds and application of fertilizer, in mandays/ha	
labcutre (y)	amount of labour required to cut trees of species y, in mandays/ha	
labcons(s)	amount of labour required to build stone bunds on land category w, in mandays/ha	(89)
labtree(p,y)	amount of labour required for planting trees of type y in period p, in mandays/ha	

lablivs(p,v) amount of labour required to tend one head of livestock v in period p

mlab(p,c) the amount of male labour needed in period p to plough one ha of land under crop c, in days

Therefore the *labour constraints* for p ∈ P, and t ∈ T, will be as follows:

$$\begin{aligned}
&\sum_{c,s,f,w} labcult(c,p) \times CLAND(c,s,f,w,t) \\
&+\sum_{s} (labcons(s) \times [CSTONE(s,p,t) + TSTONE(s,p,t)]) \\
&+\sum_{tt=0}^{t-1} \sum_{s,w,y} labcutr(y) \times TCLAND(s,w,y,tt,p,t) \\
&+\sum_{s,w,c,f} (labfert(p,f) \times CLAND(s,w,c,f,t) \\
&+\sum_{v} labliv(v,p) \times LIVSTK(v,t) + \sum_{s,w,y} labtree(y,p) \times TLAND(s,w,y,t,t) \\
&\leq avlbal(p,t) - OFFARM(p,t)
\end{aligned} \tag{90}$$

$$\begin{aligned}
&\sum_{c,s,f,w} mlab(p,c) \times CLAND(c,s,f,w,t) \\
&+\sum_{tt=1}^{t-1} \sum_{s,w,y} labcutr(y) \times TCLAND(s,w,y,tt,p,t) \times TCLAND(s,w,y,tt,p,t) \\
&+\sum_{s} (labcons(s) \times [CSTONE(s,p,t) + TSTONE(s,p,t)] + OFFARM(p,t) \\
&\leq avmlbag(p,t)
\end{aligned} \tag{91}$$

i.e. the total amount of labour required in period p for the cultivation of the total cropland, keeping livestock, constructing stone bunds and planting trees should not exceed the total labour available in the village less the labour spent on off-farm jobs. In addition, the amount of male labour required to cultivate the cropland should be less or equal to the availability of male labour in each period minus labour spent on off-farm jobs.

6.11 Cash constraint

The sources of cash to the typical farmer in the highlands of Eritrea include, selling livestock and livestock products, selling crops, off-farm employment, and remittances. Although due to lack of collateral rural households have very limited access to credit, we also include the possibility of credit. Cash not spent in a given year is carried over to the following years. The major expenditures in rural areas include consumer goods and services as well as some farm inputs. The average per capita expenditure on non-cereal items is estimated based on our findings during the field work. Households earn cash from the sale of crops, livestock and from non-farm activities. The selling and buying prices are different mainly due to transport, storage and other marketing costs (see 7. 10). The amount of money rural households spend in any given year should not exceed their earnings during the year and saving from previous years. We assume that prices as well as the wage rate remain the same throughout the planning period. We first define the following decision variables and parameters for $c \in C$, $v \in V$, and $t \in T$:

CASHBAL(t) cash remaining at the end of year t, after all expenses are paid, in Nakfa
CREDIT(t) amount of cash the village borrows in year t, in Nakfa
PAYCREDIT(t) amount of money paid in year t in settlement of loans plus interest in year t
INTEREST(t) amount of money paid as interest in year t
cash0 total amount of cash available in the village at the beginning of the planning period
bpricec(c,t) buying price of crop c in year t, in Nakfa/kg
spricec(c,t) selling price of crop c in year t, in Nakfa/kg
priceu(t) price of Urea in year t, in Nakfa/kg
priced(t) price of DAP in year t, in Nakfa/kg
bpricev(v,t) buying price of livestock v in year t, in Nakfa/kg (92)
spricev(v,t) selling price of livestock v in year t, in Nakfa/kg
pricem(t) price of milk in year t, in Nakfa/litre
bpricew(t) buying price of fuel wood in year t, in Nakfa/kg
spricew(t) selling price of fuelwood in year t, in Nakfa/kg
pricek(t) price of kerosene in year t, in Nakfa/litre
wage(t) wage rate in year t, in Nakfa/person/day (from off-farm jobs)
remit(t) average amount of money households receive from relatives in one year in year t, in Nakfa
hhexp(t) amount of money required to buy basic non cereal items such as oil, salt, sugar, etc in year t, in Nakfa/year/person
r the rate of interest

The cash balance for the village at the end year t for $c \in C$, $v \in V$, $y \in Y$, and $t \in T$, $t \neq 1$ is given in (93).

$$
\begin{aligned}
CASHBAL(t) = CASHBAL(t-1) &+ \sum_{c} spricec(c,t) \times SELLCROP(c,t) \\
&+ \sum_{v} spricev(v,t) \times SELLLIVSTC(v,t) + \\
&+ \sum_{y} pricew(y,t) \times SELLWOOD(y,t) \\
&+ \sum_{p} wage(t) \times OFFARM(p,t) + CREDIT(t) \\
&+ pricem(t) \times milk(t) + remit(t) \\
&- \sum_{c} bpirce(c,t) \times BUYCROP(c,t) \\
&- \sum bpricev(v,t) \times BUYLIVSTC(v,t) \\
&- \sum_{y} bpricew(y,t) \times BUYWOOD(y,t) \\
&- pricek(t) \times KEROSENE(t) - priceu(t) \times BUYUREA(t) \\
&- priced(t) \times BUYDAP(t) \\
&- PAYCREDIT(t) - hh\exp(t) \times POPL(t)
\end{aligned}
\tag{93}
$$

Equation (93) will also hold for t = 1, if the first term in the right hand of (93) is replaced by *cash0*. (94)

We assume that credit obtained in any given year plus interest will be paid in the following three years in equal instalments. Thus for all t ∈ T:

$$\sum_{t} PAYCREDIT(t) = \sum_{\tau=t-3}^{\tau=t-1} 1/3 \times (1+3r) \times Credit(\tau) \tag{95}$$

We will also postulate that credit cannot be obtained in the last two years of the planning period because there will not be sufficient years to settle the credit. Thus,

$$CREDIT(t) = 0 \text{ for t = T-1, T-2} \tag{96}$$

The amount of interest paid in year t for all t ∈ T is given in (97)

$$INTEREST(t) = \sum_{\tau=t-3}^{\tau=t-1} r \times CREDIT(\tau) \tag{97}$$

6.12 Land management, crop yield, soil and nutrient loss

Crop yield is one of the most important parameters in our model. Crop yield is influenced by a number of factors such as the amount and distribution of rainfall, soil type, and application of fertilizer. While rainfall is an exogenous factor, soil depth, the type and quantity of fertilizer applied, as well as the intensity and frequency of farm activities (such as ploughing and weeding) are influenced by the decisions of farming households. The estimation of crop yield for different crops where all the above factors are variable is very difficult. Thus we obtain crop yield under average conditions of rainfall and labour input (for land preparation, weeding and harvesting) and concentrate on the effect of soil type, construction of stone bunds, and the application of different types of fertilizer, which are of prime importance to our study. The relevant parameters are derived in Chapter seven.

Soil type and the type of crops cultivated as well as the construction of stone bunds and application of various types of fertilizers also influence the amount of soil and nutrient loss, which are used as indicators of the sustainability of production systems. See Chapter seven for discussion on the relationships between soil and nutrient loss on the one hand, and the type of land, crops cultivated and various management practices on the other. For $s \in S$, $w \in W$, $c \in C$, $f \in F$, $y \in Y$, $t \in T$, we define:

erosc(s,w,c,f)	rate of soil loss from land of soil type (s,w), cultivated with crop (c,f), in tons/ha/year	(98)
erost(s,w,y)	rate of soil loss from land of soil type (s,w), planted with tree species y, in kg/ha/year	
TSLOSS(t)	total amount of soil loss in year t, in tons	

For $s \in S$, $w \in W$, $c \in C$, $f \in F$, $y \in Y$, $t \in T$, the total amount of soil lost in year t can be written as follows:

$$\begin{aligned} TSLOSS(t) = & \sum_{s,w,c,f} erosc(s,w,c,f) \times CLAND(c,s,f,w,t) \\ & + \sum_{s,w,y,tt} erost(s,w,y) \times TLAND(s,w,y,tt,t) \end{aligned} \tag{99}$$

Similarly the rate of nutrient loss is influenced by type of land, land use, and land management techniques. Nutrient balance refers to the difference between nutrient inflows and nutrient outflows from a given land. The major sources of nutrient inflow are the application of mineral and organic fertilizers, nutrient deposition by rainfall, inputs of nutrients due to soil sedimentation and nitrogen inputs due to N-fixation. Outflow of nutrients on the other hand include removal of nutrients due to harvest of crops and residues, leaching of nutrients, nitrogen gaseous losses and nutrient losses due to soil erosion. In this study we focus only on the nitrogen balance. The processes involved in nitrogen inflows and outflows and the parameters associated with each process are described in Chapter seven.

We define the following variables and parameters for all $t \in T$

NBAL(t)	Average nitrogen balance in year t, in kg/ha	
ncontf(f)	amount of nitrogen in fertilizer type f, in kg	
ncontc(c)	amount of nitrogen in crop and crop residue in kg/kg	(100)
nrain	amount of nitrogen supplied by rainfall in year t, in kg/ha	
nfix	amount of nitrogen supplied due to nitrogen fixation, in kg/year	
nfal	amount of nitrogen supplied by fallow land, in kg/year	
neros	the amount of nitrogen lost through erosion in kg/tons	

Nitrogen balance on crop lands for all $t \in T$, is given as follows:

$$
\begin{aligned}
NBAL(t) = &\Big(\sum_{s,w,c,f} CLAND(s,w,c,f,t) \times ncontf(f)\Big) / \sum_{s,w,c,f} CLAND(s,w,c,f,t) \\
&+ nrain + nfix + nfal \\
&- \Big(\sum_{s,w,c,f} ncontc(c) \times CLAND(s,w,c,f,t)\Big) / \sum_{s,w,c,f} CLAND(s,w,c,f,t) \\
&- \Big(\sum_{s,w,c,f} neros \times erosc(s,w,c,f,t) \times CLAND(s,w,c,f,t)\Big) / \sum_{s,w,c,f} CLAND(s,w,c,f,t)
\end{aligned}
\tag{101}
$$

6.13 Objective function

As stated in Chapter four, farmers have multiple objectives and they maximize net discounted income only when other objectives are met. Thus we have included the objectives of securing sufficient food for the family and sufficient energy for cooking as constraints in the model. Now we write the farmer's objective of maximizing net benefits from his farming and other activities. The Net benefit of the farmer is defined as the difference between his total earnings from sale of crops, livestock, milk and wood (adjusted for changes in stock of livestock and wood) as well as income from off-farm employment and expenditures on purchased inputs and kerosene.

For all $c \in C$, $v \in V$, $y \in Y$, and $t \in T$, we define net benefits as:

$$
\begin{aligned}
NETBENEFIT(t) = & \sum_{c} spricec(c,t) \times SELLCROP(c,t) \\
& - \sum_{c} pricec(c,t) \times BUYCROP(c,t) \\
& + \sum_{v} spricev(v,t) \times SELLIVSTCK(v,t) \\
& - \sum_{v} bpricev(v,t) \times BUYLIVSTCK(v,t) \\
& + \sum_{v} spricev(v,t) \times [LVSTK(v,t) - LVSTK(v,t-1)] \\
& + \sum_{y} \ spricew(y,t) \times SELLWOOD(y,t) \\
& - \sum_{y} bpricew(y,t) \times BUYWOOD(y,t) \\
& + \sum_{y} spicew(y,t) \times [VWDWDL(y,t) - VWDWDL(y,t-1)] \\
& + pricem(t) \times MILK + wage(t) \times OFFARM(t) \\
& - priceu(t) \times BUYUREA(t) - priced(t) \times BUYDAP(t) \\
& - pricek(t) \times KEROSENE(t)
\end{aligned}
\tag{102}
$$

The farmer will maximize the discounted net benefits. Thus we write the objective function, for t ∈ T, as follows: c ∈ C, v ∈ V, w ∈ W, f ∈ F and t ∈ T:

c ∈ C, v ∈ V, w ∈ W, f ∈ F and t ∈ T:

$$
\text{Max } \sum_{t} (1/(1+r))^{t} \times NETBENEFIT(t) \tag{103}
$$

A summary of the linear programming model, which includes as well references to the definitions of variables and parameters and to values of parameters, is presented in appendix 1 (Table A1). All the equations of the model are also presented.

Chapter 7

Estimating Model Parameters

7.1 Introduction

Before analysing land use and land management decisions of farmers in the Central Highlands of Eritrea, we first discuss the estimation of parameters of the dynamic mathematical model discussed in the previous chapter. The parameters include availability of land and labour; labour and other inputs required in different periods of the year; crop and biomass yields for various land categories and technologies; livestock characteristics; consumption patterns in rural areas and various prices. Estimation of these parameters is based on both primary and secondary data. Primary data we gathered during the field research is discussed in Chapter five. Secondary data come from many resources such as published and unpublished reports of various ministries and research stations in Eritrea, relevant literature from neighbouring countries and regions with similar characteristics as well as data generated by making use of simulation models developed in international research institutions (Hengsdijk, 2003).

7.2 Land

Classification of land into different land categories was done by land use experts from the Eritrean Ministry of Land Water and Environment. The land classification system used by the above mentioned land use experts is based on a widely used system of land evaluation developed by the United States Department of Agriculture. The classification is mainly based on soil depth and slope and indicates the extent of physical limitations of a given land to crop growth. According to this system land is classified into eight groups. For the purpose of our analysis, however, the number of land categories is reduced to four groups. The slope and soil depth range of each land category is given in Table 7.1, which also shows the size of land under each land category in the study villages[25].

[25] Soil depth varies with a given slope as well. However such detailed classification of land types was not possible. Thus the land classification is basically done based on slope and the average soil depth for each slope category was determined.

Table 7.1 Total land areas in these study villages by land type

Land Categories	Slope	Soil depth (cm)	Area of Land (ha)		
			Embaderho	Maiaha	Zibanuna
S1	0 - 8 %	> 100	88.87		604.06
S2	8 – 16 %	25-50	511.59	68.13	109.23
S3	16 – 30 %	< 25	1690.51	225.82	62.35
S4	> 30 %	< 25	20.74	727.77	0.00
Residential			67.95	16.22	42.80
Dams			23.40	0.00	10.84
Total Area			2403.06	1037.94	829.28

Source: Field measurements by MWLE staff (2002).

At present there are almost no native woodlands in Embaderho and Zibanuna and no eucalyptus plantations in Maiaha. The total area of plantations in Embaderho and Zibanuna are 46.9 ha and 21.5 ha respectively. Acacia woodlands in Maiaha were estimated to cover 50 percent of the total land.

7.3 Labour supply and requirement

In this section we discuss how the parameters relating to the availability of labour and labour requirements for crop, livestock and other activities were obtained.

7.3.1 Labour supply

The total number of people in the study villages, the age and gender composition, number of religious holidays in which agricultural activities could not be done and the length of the period under consideration determine the availability of labour in each period.

Population size and composition

The total number of people and household composition of the three subregions of the Central Highlands of Eritrea are presented in Table 5.2. The total population in the three study villages, Embaderho, Maiaha, and Zibanuna is also reported in Section 5.3.2. On the basis of the age and gender composition presented in Chapter five, we derive the total number of working people, number of adult persons and adult male persons for the above three villages.

The demographic characteristics of the three study villages are similar. It has been described in Chapter five that, on average, about 29 percent of the population are children below 10 years of age and 4.7 percent are older than 75.

Thus total number of working persons is about 66 percent of the total population. Adults refer to people between the ages of 18 and 75 and this is 38 percent of the population. Both household size and family composition vary considerably for the male-headed and female-headed households. To estimate the number of adult male labour we first distinguish between male and female-headed households. Male-headed households constitute 70 percent of the households (Table 5.5). These households are composed of 50 percent males and 50 percent females. Female-headed households constitute 30 percent of the households and are characterised by lower family size and lower number of adult males. We assume that 20 percent of the persons in a female-headed household are males.

Thus the proportion of adult male population in a village will be (0.7 * 0.5 * 0.38) for the male-headed households plus (0.2 * 0.30 * 0.38) for female-headed households. This results in 0.156 (15.6%) adult males in the population. The total number of people, number of working persons, number of adult persons and number of adult male persons in Embaderho, Maiaha and Zibanuna are presented in Table 7.2

Table 7.2 Labour availability

Village	Number of People (a)	Number working persons[1] (b)=(0.66*a)	Number of adult persons (c)=(0.38*a)[2]	Number of adult male persons D=(0.155*a)	Working time: fraction of available time (%)
Embaderho	5600	3696	2128	872	0.48
Maiaha	654	432	249	102	
Zibanuna	1480	977	562	229	

1 people between the age of 10 and 75 years old
2. people with the age of 18 and 75 years of old
Source: Based on own field survey (2002).

Religious holidays and labour availability

The total amount of labour available in each period has to be adjusted for the number of days in each period as well as for the number of days households are not allowed to undertake agricultural activities due to religious holidays. The total number of days in a given period will be 15 or 30 days (see 6.2). As discussed in Chapter five (Section 5.4), most agricultural activities such as ploughing, weeding, harvesting and threshing cannot be done during religious holidays. The religious holidays include all weekends and at least 10 other days dedicated for saints every month. But there may be overlapping between these days and the weekends. The number of days that overlap with the weekends range from one to four depending on the day the month starts and is on the average 2.86. The average number of weekend days in a month of 30 days will be 8.57 = (8/28 * 30). The number of days dedicated for saints in each month will be 7.14 = (10 – 2.86). Thus only 48 percent of the total days in each period will be available for agricultural activities[26].

7.3.2 Labour requirements

Labour requirement for cropping activities

Labour required for various agricultural activities varies considerably between the wet and dry season. The average labour requirement for the major agricultural activities in the study villages is discussed in Chapter five (see Table 5.8). The crop calendar, which describes the periods during which each activity should be carried out, is also presented in figure 5.1. The total labour requirement for undertaking the major agricultural activities in each period is calculated based on the above information. Oxen requirements are related to the various agricultural activities. The current crop production system indicates that two oxen days are required for every manday involved in ploughing or threshing.

Labour requirements for the application of manure, and stone bunds were not estimated from the survey. We describe the procedure we followed to arrive at estimates in the following sections.

Labour requirement for stone bunds

The amount of labour required for constructing stone bunds per unit area depends on the distance between bunds, which in turn, depends on the slope of the land. Assuming a one meter vertical interval[27], the length of stone bunds (km/ha) and the total number of mandays required per ha of land for the different land categories are presented in Table 7.3. The work norm for forestry activities from the Department of Land and Crop Production in the Ministry of Agriculture indicates that the construction of stone bunds require 125 mandays/km plus 20 mandays/km for maintenance (MOA, 2001).

---

[26] This is in fact a conservative estimate because a number of holidays that are observed annually are not included. Also, while some more holidays are observed in each locality, only holidays universally observed in the Highlands are included.

[27] Hurni (1985) suggests that a vertical interval of twice the depth of a workable soil. As the soils in the Highlands of Eritrea are very shallow, however, this leads to spacing that is too narrow to be practicable.

Table 7.3 Labour requirement for constructing stone bunds on different land categories

Slope category (%)	Mean slope (%)	Distance between bunds (m)	Length of structure (km/ha	Labour input mday/ha
0-8	4	25.0	0.4	50.0
8-16	12	8.3	1.2	174.0
16-30	23	4.3	2.3	333.5
> 30	37.5	2.7	3.8	543.8

Source: Based on MOA (2001).

Labour requirement for transportation

The number of man and animal days required to transport crops, crop residues and manure depends on distance of croplands from the homestead and on the means of transport. Most of transport activities are done by donkeys. Following Hengsdijk *et al.* (1996), we assume a 100 kg capacity per trip and four trips per day.[28] This results in a maximum daily transport capacity of 400 kg per donkey per day. The transport will also involve one person. Thus 0.25 mandays and 0.25 donkey-days are required to transport of 100 kg of crops, crop residues or manure.

Labour requirement for livestock activities

Labour requirements for livestock activities depend to a large extent on the size of herd, production situation (restricted or open grazing), as well as grazing systems practised, i.e., the distance to the pasture and seasonal migration. Rural households in most of the villages in the Central Highlands form groups and keep their livestock in rotations. Observations during the fieldwork show that one person keeps up to 50 sheep/goat or 25 cattle. This is equivalent to 0.02 persons/day/animal for sheep and goats and 0.04 persons/day/animal for cattle. We will also use 0.02 persons/day/animal for donkeys.

Labour requirement for tree planting

According to the work norm for forestry activities of the Department of Land and Crop Production in the Ministry of Agriculture, the activities required and number of mandays needed to undertake various activities related to tree planting are seedling production: 30 seedlings per manday, preparing pits: 25 pits per manday, and planting: 70 plants per manday. It is also the norm of the department to plant 2000 seedlings per ha which results in labour requirements of 66.67, 80.00 and 28.57 mandays per ha for seedling production, pitting and planting respectively. The above activities are not required for acacia woodlands, which are assumed to regenerate naturally.

[28] This is based on an average speed of 4 km per hour, 6 working hours per day and an average village-field distance of 3 km.

Labour requirements for cutting of trees is assumed to be 500 mandays/ha and 200 mandays/ha for eucalyptus plantations and natural woodlands respectively. Both the density and size of trees in plantations is often larger in Eucalyptus plantations than on acacia woodlands.

7.4 Crop yields and agricultural technologies

Understanding the relationship between inputs and outputs of different agricultural activities is crucial in analysing the economic and environmental impacts of new technologies and policy instruments. Agricultural activities result in desirable outputs such as grain yields and crop residues and undesirable outputs such as soil erosion or nutrient depletion (van Ittersum and Rabbinge, 1997). As we have seen in the previous chapters, the interactions between socio-economic and biophysical conditions are complex and the analysis requires both socio-economic data such as resource endowments, prices and infrastructure as well as biophysical data that determine the actual and potential production activities. Quantitative analysis is needed to disentangle the complex relationships involved. Thus, technical options for crop and livestock production have to be defined in terms of input-output coefficients (Hengsdijk and van Ittersum, 2002). For example, coefficients that relate technical options such as stone bund, mulching and fertilizer on the one hand and outputs such grain yield, soil loss and nutrient balance on the other are required to analyse the economic and environmental impacts of each option.

For production activities and technologies applied in practice, coefficients that relate inputs to some outputs (e.g. crop yield) can be derived from econometric analysis of empirical data collected using field surveys. Input-output coefficients for alternative technologies, and coefficients that relate inputs to outputs that cannot be easily measured in field surveys (e.g. nutrient balance), on the other hand, can be derived only from field experiments or agro-ecological simulation procedures. There are very few experimental results in Eritrea that can provide us with data required for this study.

This section discusses how the input-output coefficients required in this study are derived. Most data relating to crop and livestock activities are based on a Technical Coefficient Generator (TCG) developed for the highlands of Northern Ethiopia (Hengsdijk, 2003). Empirical data relating to Eritrea are analysed and presented in Section 7.9 for purposes of comparison and to obtain additional data. We first provide a description of the TCG.

7.4.1 The Technical Coefficient Generator

The TCG is a model that enables to structure basic knowledge and data in order to quantify the inputs and outputs of alternative land use systems (Ruben *et al.,* 2003; Hengsdijk, 2003). The TCGs generally use a 'target-oriented' approach for quantification of inputs and outputs. That is, TCGs determine the technically optimal combination of inputs required to achieve a predetermined production level (target output). These predetermined production levels vary from maximum yields, which is the potential yield for given climate, soil and crop characteristics, down to very low yield levels.

Potential yields are first estimated, using a crop growth simulation model for given climatic conditions, while other conditions such as nutrient availability and land management being optimal. The WOFOST model, which is a quantitative model that simulates growth in time and production of annual crops based on various sets of crop parameters, soil characteristics and daily meteorological data, is used to estimate the potential yields for the TCG.

In order to estimate potential yields in a given physical environment and actual yield levels under various constraints, the TCG uses the concept of hierarchical yield levels. Actual yield levels are classified as a function of different production factors i.e., growth-defining (e.g. temperature), growth-limiting (water or nutrients) and growth-reducing (e.g. pests or weeds) (Hengsdijk and van Ittersum, 2002). The structure of the TCG developed for northern Ethiopia (TCG-Tigray) and the calculation rules applied are largely based on TCGs earlier developed for Mali and Costa Rica (Hengsdijk *et al.,* 1996; 1998). We will describe the main features the TCG-Tigray and the type of data it generates.

The design of TCGs, i.e., the choice of activities and technologies to be included, depends on the characteristics of the physical environment as well as socio-economic and environmental objectives. Choice must be made between the large number of activities (e.g., types of crops included) and various production techniques to be included. Depending on whether the objectives have a socio-economic character, or environmental one such as reducing soil erosion, alternative management criteria that refer to the ratio between labour and capital, or soil conservation techniques resulting in different levels of soil loss need to be included. Table 7.4 provides the definition criteria of various crop systems in TCG-Tigray and the variants included in rain-fed cropping system.

Table 7.4 Design criteria for various cropping options in TCG

Attribute	Design criteria	Number of variants
Physical environment	Zone	Two different zones can be selected, with different soil types and climate
	Type of rainfall year	Three years for the first zone and Sixteen years for the second zone can be selected representing different levels of rainfall
	Soil type	Eleven soil types based on slope, soil depth and presence of stones: six for the first zone and five for the second zone
Plant type	Crop types	Five crops: Sorghum, wheat, barley, pulses and millet
	Production level	Nine yield levels: potential yield is reduced stepwise with 10% until a minimum of 20% of the potential yield
Production techniques	Sowing dates	Twelve separate sowing dates can be selected
	Mechanization level	Two levels of mechanization: low, manual field operation and high, animal traction
	Crop residue strategy	Three strategies: field grazing and burning of residues, mulching, and harvesting residue for feeding cattle
	Weed Control	Two strategies: manual weeding and use of herbicides
	Pest and disease control	Two strategies: no biocides and use of biocides
	Soil conservation measures	Two strategies: no bunds and stone bunds

Source: Based on Hengsdijk (2003)

As the soil types in the TCG-Tigray did not fit the land classification in this study and because we wanted to use the model to generate data for three villages with different altitude and rainfall levels, it was necessary to make some adjustments. Thus, new levels of potential yields were generated using WOFOST for land types s_1 to s_4 (see Table 7.1) and for each study village.[29] In addition, higher level of rainfall is selected in generating the data for Zibanuna compared to the rainfall levels used in the cases of Embaderho and Maiaha.

[29] Note that WOFOST is not an integral part of the TCG. Only potential yields determined by WOFOST simulations are included in the TCG.

The options considered in this study include four soil types[30], one mechanization level (animal traction), two crop residue strategies (mulching and harvesting residues), one weed control method (manual weeding), no use of biocides and two conservation methods (stone bund and no stone bund). Nine different levels of target output were also set, ranging from 20 percent to 100 percent of the water-limited yield level and the inputs (N, P, and K) required to achieve each target yield under various crop residue strategies and soil conservation methods were generated by the TCG. This way the inputs and outputs for different combinations of land management and soil types were generated for the major crops in the Central Highlands of Eritrea: barley, wheat, sorghum, millet and beans[31]. In total, 144 different combinations of inputs and outputs were obtained for each crop. The inputs used in the analysis include nutrients N, P, K, quantity of biomass used as mulch, and stone bunds. The outputs on the other hand include desirable output such as grain and crop residues and undesirable ones such as soil erosion and nutrient losses.

While the TCG-Tigray generates crop yields, crop residues and soil loss, it does not generate nutrient losses. The procedure in the TCG, as previously stated, is a target-oriented approach and can be described as follows: First nutrient outflows from the system due to various reasons (erosion, leaching, volatilization) and nutrient inflows from natural sources (such as atmospheric deposition and N -fixation) are estimated. Then for each level of target yield, nutrients that will be taken up by crops and crop residues are estimated and nutrient inputs requirement that will make up for the differences between total nutrient inflows and outflows are determined. The implication in the above procedure is that in/outputs of nutrients are always in balance. Also if there are no nutrients there will be no or too little yield. However, the actual practice in the Highlands of Eritrea is that farmers generally apply little or no fertilizer, which implies a decline in the stock of nutrient in the land (soil mining).

To arrive at reasonable estimates of yields for different levels of fertilizer application, and to be able to estimate changes in nutrient balance on croplands, it is necessary to take into account the uptake of nutrients by crops from the pool of nitrogen in the soil. This will be discussed in Section 7.5.2. In the next section we present a statistical estimation of yield functions based on the data generated using the TCG.

[30] Detailed soil characteristics required by the TCG were not possible to obtain for the study villages.
[31] Taff is not included in the TCG. The coefficients for taff are assumed to be the same as for barley.

7.4.2 A statistical analysis of results from TCG

Ruben and Ruijven (2001) point to limitations of simulation models and suggest Meta modelling techniques as supplementary tool. A Meta model is an approximation of the input/output transformation that is implied by the simulation model (Kleijnen 1997, p.2). A meta model may be developed for various reasons: 1) meta modelling simplifies the outcomes of simulation models, with the objective of gaining insight into the critical relationships within the simulation procedures, 2) meta models are often much smaller in size and can be used to replace the original simulation model in subsequent analysis, and 3) meta models are used for the validation and verification of the robustness of the simulation models. The first two are the main reasons for using a Meta modelling technique (from TCG simulation model of Hengsdijk, 2003) in this study.

The large number of data points generated by the TCG was statistically analysed to derive continuous functions. A Cobb-Douglas production function was fitted for each crop separately[32] as follows.

$$\ln Y = \beta_0 + \beta_1 \ln(N) + \beta_2 \ln(P) + \beta_3 \ln(K) + \beta_4 Mulch + \beta_5 Bund + \beta_6 STYPE2 + \beta_7 STYPE3 + \beta_8 STYPE4 \qquad (1)$$

Where Y represents crop yield in kg/ha, N, P, and K, quantities of nitrogen, phosphorus and potassium in kg/ha respectively, Mulch refers to the quantity of crop residue used as mulch in kg/ha, Bund is a dummy variable equal to zero for no bund and 1 for stone bund. STYPE2, STYPE3 and STYPE4 are dummy variables, which are equal to 1 if land is of soil type s2, s3 and s4 respectively, and equal to 0 otherwise. The expected sign for the coefficients of all variables are positive except for s_2, s_3 and $s_{4,}$ which are negative. The results for Embaderho village are presented in Table 7.5.[33]

The variable K in all cases had either the wrong sign or was not significant. This is probably due to the very high levels of correlation between N and K[34]. Thus the variable K was dropped from the regression. STYPE2 was not significant in the case of barely, pulses and wheat. All the remaining variables have the expected sign and are highly significant. N and P are expressed in logarithms and therefore the coefficients are elasticities. For example a one percentage change in the quantity of nitrogen applied to barley results in about 0.41 percentage change in the yield of barley. In the case of mulching, as both the options with and without the application of mulch are considered, half of the observations had zero values. Thus we did not use the logarithm form. The

[32] The Cobb-Douglas production function is used because it resulted in the best fit.
[33] The results for the Maiaha and Zibanuna are presented in Appendix 3
[34] The correlation coefficient between and N and K is 0.56.

coefficients of mulching show a percentage change in crop yield for a unit increase in the amount of crop residues applied as mulch. The coefficients of bund show the percentage increase in crop yield due to the application of stone bund. Similarly the coefficients for STYPE2, STYPE3 and STYPE4 show by what percentage crop yields from soil types s_2, s_3 and s_4 are lower than the yield of crop from soil type s_1. Adjusted R^2 is 0.94 or above for all the crops. And the D-W test is reasonable with values between 1.4 and 2.6 for all the crops.

7.5 Sustainability indicators

Soil loss and nitrogen balance are the indicators of sustainability used in this study. The relationship between land types and various land management practices on the one hand, and soil loss from croplands on the other is discussed in the following sub-section. A more detailed discussion of soil erosion including some empirical evidences from research stations in Eritrea is presented in Section 7.9. Nutrient balance is discussed in Section 7.5.2.

7.5.1 Soil erosion

Soil erosion is a complex process in which various climatic, topographic and land use and land management factors determine the rate of erosion (see Section 7.9.2). We will use the data generated by the TCG-Tigray to estimate the rates of erosion from croplands under different land management practices. As with yields, soil loss is modelled as a function of nitrogen and phosphorus application, application of mulch, application of stone bunds and soil types. Soil erosion is expected to decrease with the application of NPK, stone bunds and mulch and increase with slope of land. Thus, the coefficients of STYPE2, STYPE3 and STYPE4 are expected to be positive and the coefficients of the remaining variables are expected to be negative. The results are presented in Table 7.6.

Table 7.5 Cobb-Douglas yield functions (coefficients and t-statistics using Ordinary Least Square regression)

	Barley		Millet		Beans		Sorghum		Wheat	
	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat
C	5.0476***	38.7	4.5436***	18.48	5.3168***	90.67	4.9115***	39.29	4.5563***	42.02
ln (N)	0.4077***	5.88	0.4315***	4.00	0.1933***	7.68	0.5547***	11.12	0.6093***	12.02
ln (P)	0.2759***	4.96	0.0856*	2.0317	0.2933***	14.20	0.1427***	5.03	0.1048***	2.77
Mulch	0.0001***	15.19	0.0002***	9.79	0.0008***	11.14	0.001***	18.35	0.0001***	14.19
Bund	0.0851***	5.52	0.3599***	9.74	0.2211***	5.92	0.0891***	5.32	0.1181***	5.90
STYPE2	-0.0045	-0.34	-0.1544***	-3.76	0.0747	1.29	-0.0932***	-4.10	-0.0162	-0.93
STYPE3	-0.1948***	-8.08	-1.0615***	-11.74	-0.4928***	-9.71	-0.3579***	-11.81	-0.2857***	-12.59
STYPE4	-0.5244***	-10.1	-1.9674***	-9.46	-1.0370***	-14.65	-0.6612	-14.56	-0.7736***	-17.57
No. observ.	144		144		144		144		144	
Adj. R^2	0.98		0.94		0.94		0.96		0.97	
D-W stat	1.56		2.54		1.78		1.62		1.41	

The dependent variable is log(yield). The first three variables are also in logarithm.

D-W Stat is the Durbin-Watson Statistics

* $P < 0.05$

** $P < 0.01$

*** $P < 0.001$

Table 7.6 Soil loss functions (coefficients and t-statistics using Ordinary Least Square regression)

	Barley		Millet		Beans		Sorghum		Wheat	
	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat
C	3.1458***	42.27	2.8158***	32.93	2.5344***	84.64	2.9886***	22.27	3.2328***	51.70
ln(N)	-0.2207***	-6.48	-0.2498***	-6.79	-0.0561***	-5.29	-0.3583***	-6.1643	-0.2764***	-11.07
ln(P)	-0.0472	-1.90	-0.0070	-0.53	-0.0818***	-9.61	-0.0315	-0.7834	-0.0199	-1.20
Mulch	-0.0003***	-46.64	-0.0003***	-29.66	-0.0004***	-13.06	-0.0003***	-42.98	-0.0003***	-63.22
Bund	-0.6759***	-56.96	-0.6169***	-42.62	-0.6926***	-44.94	-0.6560***	-50.78	-0.6763***	-56.18
STYPE2	0.6086***	36.39	0.6324***	39.18	0.5873***	24.58	0.6445***	30.84	0.6126***	36.28
STYPE3	1.4744***	72.74	1.4905***	42.27	1.4996***	60.09	1.5380***	43.15	1.4839***	77.46
STYPE4	1.6275***	0.52	1.7351***	30.93	1.6290***	51.51	1.7626***	30.38	1.6736***	65.99
No. observ.	144		144		144		144		144	
Adj. R^2	0.99		0.99		0.99		0.99		0.99	
D-W stat	3.29		2.95		1.67		2.50		3.20	

The dependent variable is log (yield). The first three variables are also in logarithm.
D-W Stat is the Durbin-Watson Statistics
* $P < 0.05$
** $P < 0.01$
*** $P < 0.001$

All variables except P-fertilizer are significant for all crops at the 1% level. P-fertilizer is not significant in all cases except pulses.

7.5.2 Nitrogen balance

Nitrogen is present in the soil in different forms and various complex processes are involved that affect nitrogen balance overtime and uptake by crops at any given time. A summary model has been developed by Wolf *et al.* (1989) that describes the main processes and which could be used to predict long-term changes in nitrogen balance and plant available nitrogen.

The model distinguishes two pools of soil organic nitrogen – labile organic nitrogen (LON) and stable organic nitrogen (SON) - and four external sources of nitrogen: rainfall (NRAIN), biological fixation (NFIX), inorganic fertilizer (NFERT) and organic materials such as crop residue and animal manure (NORG). Nitrogen from external sources may be transferred to crops, to labile or stable pool, and/or lost in agricultural systems. Nitrogen from the labile pool may be transferred to crop, stable pool or lost to agricultural systems. Nitrogen from the stable pool can only be transferred to the labile pool. Fig 7.1 shows the structure of the model. For a detailed description of the model and the processes involved see Wolf *et al.* (1989).

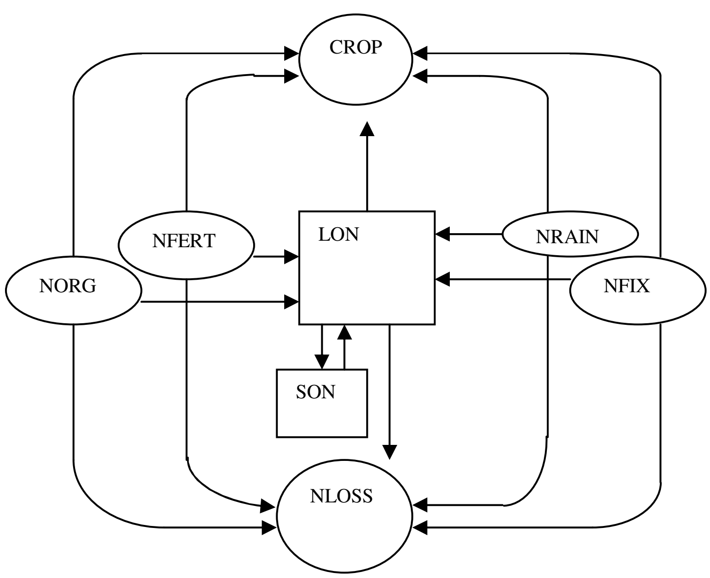


Figure 7.1 Model structure, with in the centre a labile and stable organic nitrogen pool. Nitrogen inputs from biological fixation (NFIX), fertilizer (NFERT), organic matter applications (NORG), rainfall (NRAIN), and from mineralization of LON are partitioned over crop uptake (NCROP), incorporation in the labile pool, and losses (NLOSS).
Source: Wolf *et al.* (1989)

Hengsdijk and van Ittersum (2003) have applied the model for semi-arid conditions in West Africa and tested it with a long-term data set from Saria in Burkina Faso. The model has also been applied to the Koutiala region in Mali and to Tigray region of the Highlands of Ethiopia (Hengsdijk and van Ittersum, 2003; Hengsdijk 2003). Estimations of transfer coefficients of nitrogen originated from different sources to crop uptake, incorporation to the labile pool and losses were obtained from literature and expert knowledge[35]. Table 7.7 shows the transfer coefficients, estimated levels of stable and labile pool of nitrogen, as well as estimated quantities of nitrogen from rainfall and biological fixation used in the TCG-Tigray.

Table 7.7 Annual N inputs via rain (NRAIN) and biological fixation (NFIX), and the fractions transferred to crop, labile and stable pool, and lost N via inorganic fertilizer (NFERT), organic material (NORG), biological fixation, rain and mineralized soil organic matter (LON).

	Transfer coefficients				Source of Nitrogen (kg/ha/year)			
	Crop	Loss	Labile pool	Stable pool	NRAIN (kg/mm)	NFIX (kg/ha)	Labile pool (kg/ha)	Stable pool (kg/ha)
NFERT	0.40	0.40	0.20		0.00065	2.5	222	665
NORG								
Manure	0.30	0.3	0.40					
Crop residues	0.10	0.1	0.80					
NFIX	0.15	0.15	0.70					
NRAIN	0.40	0.40	0.20					
LON	0.425	0.425	0.00	0.15				
SON	0.00	0.00	1.00					

Source: Hengsdijk and van Ittersum (2003); Hengsdijk (2003).

While all nitrogen applied from external sources (NFERT, NORG, NFIX and NRAIN) are transferred to either crop, losses and to the labile pool in the same year, only part of the nitrogen in the labile and stable pools is transferred in any given year. About 1.07 percent of the stable pool is converted every year into a labile pool. Similarly 21.46 percent of the nitrogen in the labile pool is transferred to crop, the stable pool or lost to the system. The initial sizes of the labile and stable pools are set to 222 kg/ha and 667 kg/ha respectively (Hengsdijk, 2003).

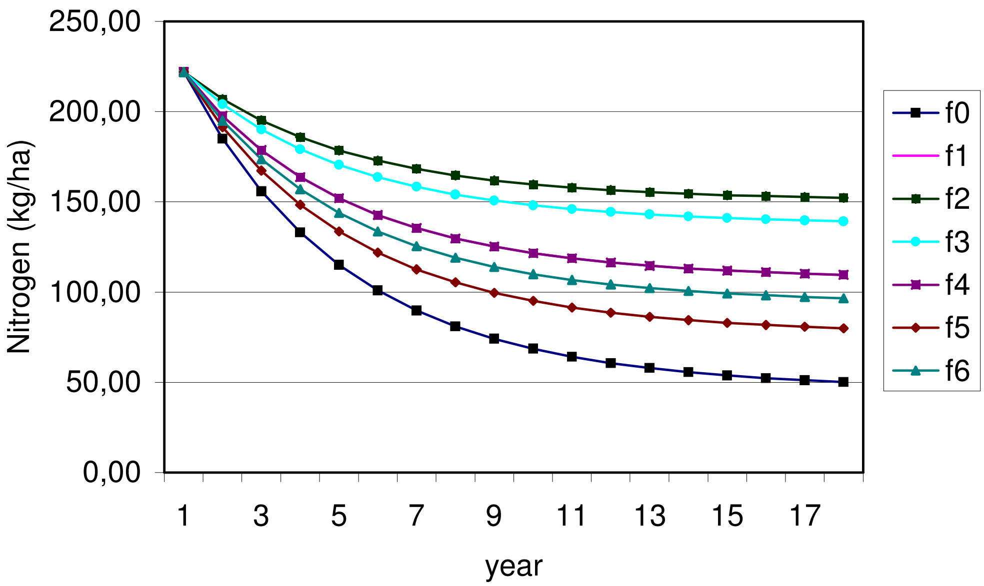
As mentioned in Section 7.4.1, the nutrient-yield relationship implied by the TCG-Tigray reflects a sustainable system in which nutrient inflows and outflows are in balance. The above discussion enables us to simulate the actual (unsustainable system) in the study area. By allowing crops to use nutrients from the pool of nitrogen in the soil, and using the yield function we have already

[35] For a detailed explanation of the estimation of these factors see Hengsdijk and van Ittersum (2003) and Wolf and van Keulen (1989).

estimated, we can arrive at the simulated actual yields. At the same time using the initial pool of nitrogen and the transfer coefficients described above, we can calculate nutrient dynamics in the soil over time.

The amount of nitrogen in the soil declines as part of it mineralises and is transferred to crops or lost due to erosion and other processes[36]. On the other hand, the nitrogen in the soil increases due to supply from external sources. The transfer coefficients for the various types of fertilizers, and hence their contribution to nitrogen balance are different (Table 7.7). As the type and quantity of nitrogen applied to a given plot varies from one year to the other, the calculation of nitrogen balance is very difficult. Thus we estimate the average annual rate of change in the nitrogen in the soil when different types and quantities of fertilizer are applied. Figure 7.2 shows the rate at which nitrogen in the labile pool declines when a certain type of fertilizer is applied.

Figure 7.2 Changes in soil nitrogen for different levels of fertilizer application[37]



[36] Nitrogen inputs from different sources are based on parameters in Table 7.7 and Table A6 (see appendix). Nitrogen loss from the soil due to crop and residue harvests is based on crop yields and parameters in Table A6.
[37] Note: f0 = no fertilizer, f1 = 1800 kg of manure, f2 = 3600 kg of manure f3 = 1800 manure + 500 kg or crop residue, f4 = 50kg Urea + 50kg DAP + 500 kg of crop residue, f5 = 50kg Urea + 50kg DAP, f6 = 100kg Urea + 50kg DAP

As shown in Figure 7.2, the application of organic fertilizers considerably reduces the depletion of nitrogen from the soil. Thus while at the fertilizer application rates considered in this study nitrogen in soil will decline, the rates of decline vary considerably when different types of fertilizer are applied.

7.6 Inputs and outputs of livestock activities

In this section we will discuss feed requirement as well as the outputs of the various types of livestock in the Highlands of Eritrea. No empirical data was available on livestock productivity and feed requirements in Eritrea. However, some values are obtained from the report of National Livestock Development Project FAO (2001), which was based on expert estimations and data from similar environments.

The TCG also provides information on livestock inputs and outputs. The simulation model is based on a stationary herd assumption in which an equilibrium livestock system is described, i.e. a system in which the inputs and outputs are identical each year. Both the herd structure (age and sex composition) as well as the selling strategy of the farmers is specified in such a way that the size and composition of the herd remains the same through time. The model generates feed requirement, milk production and live weight increase for sheep, goat, and cattle.

Live weight gain

As farmers in rural Eritrea sell live animals and not meat, we use the live weight gain to estimate the annual rate of growth in the various types of livestock or the off take rate which is the maximum level of extraction at which the population of livestock can be maintained. If we assume the weight composition of the livestock remains the same, then a live weight gain of the total herd of animals will be due to an increase in their number. Column 2 in Table 7.8 shows the average weight of the herd of different types of livestock, which includes adult animals as well as young ones. Column 3 shows live weight increase per TLU of each type of livestock. The figures in brackets are percentage increase in the number of animals, which are calculated by dividing the live weight increase by 250 (which is the average weight of one TLU) and multiplying by 100[38].

[38] The weight of the additional livestock produced will also be the same as the average weight. Thus the market price of each type of livestock (which often reflects the price of adult animal) will be adjusted to reflect the lower average weight.

Table 7.8 Feed requirement, milk production and live weight gain of livestock

Type of animal	Average weight (kg/animal)	Live weight gain* kg/TLU/yr	Milk Production** litres/TLU/yr	DOM Requirements** kg/TLU/yr
Goats	18.3	79.8 (31.9%)	77.7 (5.7)	1896.0 (138.8)
Sheep	21.1	68.7 (27.5%)	78.0 (6.6)	1960.6 (165.5)
Cattle	180.0	54.3 (21.6%)	125.3 (90.2)	1101.4 (793.0)
Oxen	300.0	-	-	1197.2 (1436.4)

* Figures in bracket refer to annual rate of increase in the number of livestock
** Figures in brackets refer to milk production or feed requirement per animal per year. This is based on TLU = 250 kg animal and the average weight of each type of livestock shown in column 2 of Table 7.8.
Source: Based on Hengsdijk (2003).

The estimated rates of growth for goats and sheep (31.9 and 27.5 percent respectively) seem to be reasonable compared to the FAO estimation for Eritrea of 30% and 25% percent off-take rate for goats and sheep respectively (FAO, 2001). The study maintains that a significant proportion of the goats deliver twins or triplets that the off-take rate should be a minimum of 30 percent. The 21.6% rate of growth of cattle however is extremely high when compared to the FAO (2001) estimate of 9%. Such a very low off-take rate is because the FAO estimate is based on a 20% cows in the herd composition due to the high proportion of oxen in the highlands. In our analysis however, oxen are considered as separate type of livestock and the number of male animals in the cattle are just sufficient of reproduction purposes. Thus if we assume the proportion of cows is 80 percent of the herd, then off-take rate will be much higher.

Milk production

The production of milk from goats, sheep and cattle is 5.7, 6.6 and 90.2 litres per animal per year respectively. This is considerably higher than the FAO estimates, which are 2.5 and 30 litres per annum for goats and cattle respectively. For cattle, as discussed above, this can be due to the low number of cows in the herd. If we assume cows make up 60 percent of the herd, the average annual production of milk will be 90 litres per animal, which is similar to Hengsdijk's estimate. Similarly, the FAO study assumes that milking goats constitute only 10 percent of the herd, which seems to be very low. For sheep and goats we will take an annual milk production of 6.1 litres per animal per year, which is the average of the two estimates.

Feed requirement

Maintenance energy requirement relative to live weight is higher for small compared to large ruminants. Results from Hengsdijk's agro-ecological simulation model are presented in Table 7.8. The DOM requirement per kg of live weight for sheep/goats is considerably higher than the requirement for cattle. The figures in brackets, in column 5 are feed requirement per animal per year. These are calculated for each type of animal by dividing the DOM requirement per TLU by 250 and multiplying by the weight of the respective livestock type. The above estimates are slightly higher than the DOM requirement per animal for all types of livestock estimated by FAO, which may partly explain the higher yields of milk and off-take rates[39].

7.7 Grass and wood production

7.7.1 Grass production

Rangelands in Eritrea provide most of the feed for livestock. Most of the rangeland in the country is classified as open savannah with the botanical composition reflecting both rainfall and the extent of past utilization. The situation of pasture in the Central Highlands is extremely poor mostly because, due to the declining crop yields and increasing population, livestock are pushed to less fertile steep hillsides with low potential for grazing. The annual yield of grass is influenced by rainfall and soil quality. The Agricultural Sector Review estimates the production of feed from fertile and infertile soils under different rainfall regimes as follows (FAO 1997).

Table 7.9 Model sustainable rangeland utilization.

Rainfall (mm)	DM Yield (kg/ha)		Available Feed (kg/ha)*		Stoking Rate (ha/TLU)**	
	Fertile	Infertile	Fertile	Infertile	Fertile	Infertile
200	600	300	400	100	18.6	74.0
400	1200	600	1000	400	7.4	18.6
600	1800	900	1600	700	4.7	10.6
800	2400	1200	2200	1000	3.4	7.4

TLU 250 kg live weight
DM dry matter content of forage
* Ideal minimum residue for ground cover 200 kg/ha
** Based on maintenance diet 6.2 kg DM/TLU/day = 2.232kg TLU/year and 30% utilization level

Source: FAO (1997).

We will assume that fertile soils refer to soil type s_1 and infertile to soil type s_4 in our model. We will also assume that yield declines linearly from s_1 to s_4. Thus for an average rainfall of 500 mm/year, the DM yield for s_1, s_2, s_3 and s_4 will be 1500, 1250, 1000 and 750 kg/ha respectively[40]. For the West African savannah the following equation is suggested.

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[39] FAO (2001) estimate of DOM requirement are 104.1, 104.2, 740.8 and 834.5 kg/animal per year for goats, sheep, cattle and donkeys respectively.
[40] For the West Africa savannah the follow.

$$\text{Biomass Production} = 0.15 + 0.00375R,$$
Where R is rainfall in mm

For an average annual rainfall of 500 mm, this results in a yield (2025 kg/ha/year) higher even than soil type s_1 (Stephenne and Lambin, 2001). (Later we may consider higher yields). The consumable forage of grasses is only 1/3 of the total above ground biomass (FAO, 2001; Stephenne and Lambin, 2001). We assume that yields of grass from land treated with stone bunds will increase at the same rates as the increase in crop yields shown in Table 7.5.

7.7.2 Wood production

Trees are generally more effective than grass in converting deep soil nutrients and water into biomass (Jagger and Pender, 2000). Yield of wood varies considerably due to variations in rainfall and soil type as well as the density and age of trees. The density of trees in the natural woodlands (dominated by acacia) in the Central Highlands is generally very low. Quantitative estimates on tree density and volume of wood in the natural woodlands are almost non-existent. However, one fairly detailed study of acacia woodlands that involved actual cutting and measurement of trees from a stratified sample of the woodlands as well as remotely sensed data has been done for two sub-catchments in the Central and Southern zones (Viti *et al.,* 2001). The study covers about 535 km^2 of which 52.57% was classified as woodlands. The results of this study indicate an average cover of 10% and average age of trees approximately between 6 to 8 years. The estimated average yield of woody biomass is 0.2 m^3/ha/year or, using a conversion factor of 750 kg/m^3, 150 kg/ha/year. About 60 percent of the woodland had a total stock of woody biomass of less than 1500 kg/ha and only less than 5 percent had a stock of more than 4500 kg/ha. The estimated average stock of wood was 1050 kg/ha. Openshaw (1998) presents estimations of woody biomass yields from fully stocked woodlands in Africa for different age groups and varying levels of rainfall. For the average cover and rainfall in the Highlands of Eritrea the yields estimated above are consistent with the results of this study.

The yields from eucalyptus plantations are generally higher than the natural woodlands. Despite the long history of eucalyptus plantations, however, quantitative information on yields from plantations in Eritrea is not available. Estimates in Ethiopia show that the mean annual increments on Eucalyptus plantations vary from 10 m^3/ha/year on poor sites to 57 m^3/ha/year on good soils. Senior students from the Department of Forestry at the University of Asmara were made to estimate the average yield of eucalyptus plantations in two locations in the Central zone. The age of the trees varies from 4 years to 10 years. The average yields in the two locations were 1.10 and 1.90 m^3 per ha/year

(Ermias *et al.,* 2003). These yields are much lower than the estimates of the poor sites in Ethiopia. Since eucalyptus is generally planted on steep slopes for the purpose of soil conservation, we will assume that (the average of) these figures reflect yields on soil type 4. We also assume that the yields on other soil types will vary at the same rate as the yields for crops vary across different soil types.

In addition to wood, grass also grows in natural woodlands and eucalyptus plantations. As the number of trees in natural woodlands is much lower than in plantations, the yield of grass will be higher in the former. Yield of grass from natural woodlands and eucalyptus plantations will be assumed to be 90% and 20% respectively of the yields from grasslands. This is based on the 10% cover in natural woodlands and assuming a 20% cover in plantations.

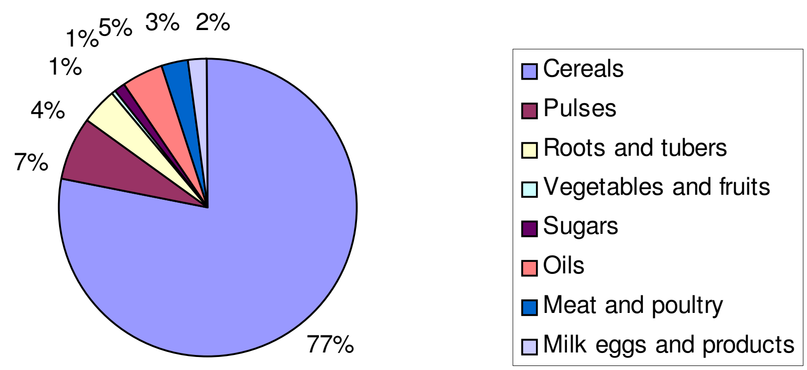
7.8 Food and fuel requirements

7.8.1 Food requirement and consumption patterns

The daily per capita energy requirements vary from one person to the other due to variations in age, sex, body weight and physical activities. Most of the data required to calculate the minimum calorie requirements in Eritrea - such as the age and sex distribution of the population, weight, birth rate, infant mortality rate, patters of physical activities and energy expenditures associated with these activities – are difficult to obtain. Some studies suggest a minimum per capita requirement of 2000 to 2050 calories per day (World Bank, 1996b).

Cereals are the basic staple in all parts of Eritrea. Figure 7.3 shows the consumption patterns in Eritrea. About 78 percent of all energy requirements are covered by cereal consumption, 7% by pulses, 5% by animal products and the remaining 10 percent from oils, sugar, roots and tubers and vegetable and fruits (FAO, 2001). In general, the costs of calories obtained from non-cereal food items are estimated to be about twice the cost of cereal calories (World Bank, 1996b). [Taking average calorie content and average price of the major cereals, the expenditures required to obtain the non cereal calories will be Nakfa 214 per person per year.]

Figure 7.3 Food consumption patterns in Eritrea



Source: FAOSTAT

Other household expenditures include expenditures for basic education, health services and other miscellaneous expenses such as purchases of clothing and soap. The average expenditure on clothing, education, health and other miscellaneous items for poor households in Asmara was estimated to be about Nakfa 100.00 per capita per year in 1996 (World Bank, 1996b). [Taking into account the high rates of inflation since the recent border war, expenditures on the above items will be about 200 per capita per year].

7.8.2 Fuel: level and composition

Traditional fuels (mainly fuel wood, dung and agricultural residues) dominate household energy consumption in Eritrea (see Chapter two). Rural households have even less access to modern fuels and heavily depend on traditional fuels. Table 7.10 below shows the contribution of different types of fuels to the total energy consumption of the rural households in the Central Highlands of Eritrea.

Table 7.10 Per capita energy consumption by fuel type for rural areas of the Central Highlands

	Zoba Debub			Zoba Maekel		
	Qty/person	% Users	MJ of energy/person	Qty/person	% Users	MJ of energy/person
Fuelwood	211.76	95.15	3344.7 (49.5)	134.07	59.41	1322.2 (28.2)
Charcoal	146.01	2.43	102.9 (1.5)	71.28	2.65	54.8 (1.2)
Dung	246.46	67.91	2008.5 (29.7)	299.74	69.4	2496.2 (53.3)
Agr. Resid	139.01	32.09	669.1 (9.9)	106.99	10.88	145.8 (3.1)
Kerosene	15.16	94.22	630.4 (9.3)	19.14	97.94	658.2 (14.1)
Electricity*	18.75	1.00	6.8 (0.1)	1.89	2.0	1.4 (0.03)
LPG	0.00	0.37	0.0 (0.0)	10.69	0.88	4.3 (0.09)
Total			6762.4			4682.7

Source: Based on MOEM (2000).

The average per capita energy use is 4682.7 MJ per year in the Central Zone and 6762.4 MJ per year in the Southern Zone. The composition of fuel also varies between the two regions of Central Highlands. Fuel wood is the dominant type of fuel in Southern zone, where it is used by more than 95 percent of the households and accounts for about 50 percent of energy consumption. Animal dung, on the other hand dominates fuel consumption in the Central zone where it accounts for more than 53 percent of energy consumption. Most households in the Central highlands use kerosene, mainly for lightening purposes. However its contribution to total energy consumption is still very low – about 9 and 12 percent in the Southern and Central zones respectively. The use of electricity and LPG is insignificant accounting for less than 1% of all energy consumption in the rural areas.

The data presented above show that per capita energy consumption increases with the availability of fuel wood and dung. Thus we will use the lower level of energy use (4682.7 MJ per person year) for Embaderho and Zibanuna and the higher level 6762.4 MJ per year) for Maiaha. Moreover, kerosene should cover at least 10% of the required energy, because at least for lighting purpose, it cannot be substituted by the other traditional fuels.

7.9 Some empirical evidences

7.9.1 Fertilizer and crop yield

Yield response to fertilizer application varies from crop to crop. It is reported that in Ethiopia maize has the highest response rate reaching up to 4 fold followed by wheat and barley, which may reach 2-3 fold increases in yields. Taff and pulses were reported to have lower rates with up to 100% and 25-50% respectively (Shank, 1996). The economically optimal rates of application, which depend on fertilizer response of crops as well as the prices of fertilizer and crops, also vary considerably from crop to crop. The following are the optimal economic rate of fertilizer application recommended by the National Fertilizer Input Unit of Ethiopia for maize, taff, sorghum, barley and wheat: 165/80, 130/110, 65/60, 100/100, 120/120 kg of DAP/Urea per ha respectively (Shank, 1996).

There are very few fertilizer trials undertaken in Eritrea. Although fertilizer trials have been underway since 1995 in different parts of the Central Highlands, only two years, 1998 and 1999 had sufficient data that would allow systematic analysis of the effect of the different rates of fertilizer application on crop yields. For other years data were not complete (Barbier, 2001; MOA 2002c). The experiments tested the effects of three levels of Urea (0, 50, 100 kg/ha) and three levels of DAP (0, 50, 100 kg/ha) with a total number of nine treatments. The mean grain yields in quintals/ha from the combined analysis of variance for 1998 and 1999 together and results of a simple economic analysis for each treatment could be found in Barbier (2001). Based on this analysis Barbier (2001) suggested a tentative fertilizer guideline for barley and wheat of 50 kg/ha Urea + 50 kg/ha of DAP to maximize the ratio of returns on cost of production. The suggested economic optimum rates of application, depending on crop and location, are 50 kg/ha DAP + 100 kg/ha Urea, 100 kg/ha DAP + 50 kg/ha Urea, 100 kg/ha DAP + 100 kg/ha. Table 7.11 presents the mean grain yields in various villages of the Central Highlands for three levels of fertilizer application.

Table 7.11 Fertilizer trials for barley and wheat in the highlands of Eritrea 1998 and 1999

Location	Barley (100 kg/ha)			Wheat (100 kg/ha)		
	1	2	3	1	2	3
Teraemni	4.2	11.2	12.3	6.2	10.6	10.8
Adigheda	7.4	11.4	12.3	8.9	13.8	14.7
Dubaruwa	-	-	-	10.4	14.5	15.7
Kisadaro	2.9	11.4	17.0	5.7	13.5	12.5
Shiketi	7.4	14.9	16.4	-	-	-
Serejeka	7.7	15.0	13.3	-	-	-
Tsaedakristian	7.5	13.1	14.4	-	-	-
Himbrti	-	-	-	11.3	17.8	18.0

1 = no fertilizer, 2 = 50 Urea + 50 DAP, 3 = 100 Urea + 50 DAP

Source: Barbier (2001).

The Soil Research Unit of the Ministry of Agriculture has also conducted extensive field level fertilizer trials for three crops (barley, wheat and taff) in various parts of the Central Highlands of Eritrea with the objectives of developing a site-specific and cost-effective fertilizer application rates. The treatments included three levels of Nitrogen (0, 30 and 60 kg/ha) and two levels of phosphorus (0, and 60, 40, 20, or 10 kg/ha) depending on the P level of each site. In total there were six treatments. Apart from some technical assistance by experts, all the trials were undertaken by the farmers under the usual farm management practices.

Both the yields from the control plots and the response to different levels of fertilizer application vary considerably due to variations in soil characteristics, rainfall and crop management. In most cases responses to fertilizer application were high, sometimes exceeding 150 % increase in crop yield. However, as the experiments represent only a single year and due to differences in soil characteristics, rainfall and crop management of the sites, no meaningful conclusions could be drawn.

Similarly, field experiments by the project Sasakawa Global 2000 indicate that the application of 50 kg Urea/ha + 100 kg DAP/ha increased yield of barley between 50 percent and 200 percent in different locations in the CH zone.

Table 7.12 Yield responses by barley to the application of 50 kg Urea and 100 Kg DAP/ha on non-vertisols in Zoba Debub, 1998, Sasakawa Global, 2000.

Sub-Zoba	Yield without fertilizer (100 kg/ha)*	Yield with Fertilizer (100 kg/ha)	
		Mean	Range
Adikeih	6	15	12-20
Senafe	6	18	15-22
Segeneiti	6	17	14-22
Mendefera	6	19	16-22
Areza	6	9	6-14
Dekemhare	6	16	12-20

* Figures are not actual measurements but average yields of the region
Source: Barber (1998)

Despite high variations the limited available evidences show a substantial fertilizer response in the Central Highlands of Eritrea. The fertilizer response of crop yields implied by the yield functions estimated using simulated data (Table 7.5) is in the range of 130 to 250 percent increase. This is considerably higher than the limited evidence from fertilizer trials presented in this section. Thus the crop yields with the use of fertilizer obtained using the TCG were reduced by 40 percent to reflect fertilizer responses under current land management practices.

7.9.2 Estimation of soil loss and run-off

In this section we will combine long-term data from Afdeyu Research Station with a soil erosion simulation model to estimate soil loss and water run-off from the different land categories described in Table 7.1. Soil loss and run-off will be estimated for croplands, grasslands and woodlands. In the following section we will make use of the estimated soil loss and run-off to calculate the impact on crop yield of the construction of stone bunds.

In Section 7.5.1, we have presented a statistically estimated soil loss from croplands using simulated data. However, the simulation model does not provide data for non-croplands. Thus the purpose of this and the next section is: 1) to extrapolate soil loss to other land uses (grasslands and woodlands), 2) compare simulated soil loss with the limited empirical evidence in the Central Highlands, and 3) to estimate impacts of stone bunds on crop yield based on field data which will serve to validate the relationship obtained by statistical analysis of simulated data in 7.4.2.

Soil loss

Accurate measurement and prediction of the rate of soil loss is the first step in estimating the costs of soil erosion and the benefits from undertaking measures to curb erosion. The level of soil erosion in a given area is influenced by a number of factors including rainfall, soil type, topography, and land use and land management. Given the gradual nature of the process, the difficulties in differentiating between the natural and accelerated rate of erosion, and the complexities of temporal and spatial variation, the physical measurement of soil erosion is extremely difficult (Lal, 1990; Eaton, 1996).

Soil erosion is generally more acute in tropical areas where rainfall is more intense and soils are highly erodible due to the relatively shallow depth and low structural stability (Eaton, 1996). However, little reliable evidence exists about the magnitude of the problem. Lutz *et al.* (1994: 274) remarked that aggregate quantitative measures about the extent of land degradation in Latin America "often have weak empirical basis and the studies have generally been scattered and unsystematic". Blaikie (1985) also presented a number of reasons for the absence or unreliability of data on the rate of soil loss in developing countries including lack of trained manpower and sophisticated equipment, which are necessary for a direct measurement of soil loss.

To overcome the difficulties and shortcomings of direct measurements statistical modelling of the process of erosion was developed that can be used to estimate soil loss based on climate, topography, soil properties and land use conditions of an area. The Universal Soil Loss Equation (USLE)[41] has been the most widely used erosion model to predict soil loss (Wischmeier and Smith, 1978) for decades. The parameter values of the factors included in the USLE (R,K,L,S,C, and P) are location specific and need to be calibrated to the specific area to enable reasonable prediction of the rate of soil loss. Hurni (1988) has modified the USLE to fit the Ethiopian conditions (Table 7.13). We will first present the USLE modified for the Ethiopian conditions and use it to extrapolate the soil loss measured in Afdeyu Research Station to lands of different slope classes and land uses.

[41] A Revised Universal Soil Loss Equation (RUSLE) has been developed to improve the USLE and address its criticisms (Renard *et al.,* 1996).

The equation is given as follows:

A = R*K*L*S*C*P
Where:
A = Soil loss (tons/ha/year)
R = Rainfall erosivity
K = Soil erodibility
L = Slope Length
S = Slope gradient
C = Land cover
P = land management

Table 7.13 The Universal Soil Loss Equation adapted for Ethiopia

R: Rainfall Erosivity								
Rainfall (mm)	100	200	400	800	1200	1600	2000	2400
Factor R	48	104	217	441	665	890	1115	1340
K: Soil Erodibility								
Soil Colour	Black	Brown	Red	Yellow				
Factor K	0.15	0.20	0.25	0.30				
L: Slope Length								
Length (m)	5	10	20	40	80	160	240	320
Factor L	0.5	0.7	1.0	1.4	1.9	2.7	3.2	3.8
S: Slope Gradient								
Slope (%)	5	10	15	20	30	40	50	60
Factor S	0.4	1.0	1.6	2.2	3.0	3.8	4.3	4.8

C: Land Cover	Land Cover	Factor C	Land Cover	Factor C
	Dense forest	0.001	Dense grass	0.01
	Other forest	0.02	Degraded grass	0.05
	Badlands hard	0.05	Fallow Hard	0.05
	Badlands soft	0.04	Fallow Ploughed	0.60
	Sorghum, Maize	0.10	Ethiopian Taff	0.25
	Cereals	0.18	Continuous fallow	1.00
	Pulses	0.15		

P: Management	Land Management	Factor P	Land Management	Factor P
	Ploughing up and	1.00	Ploughing on contour	0.90
	down	0.80	Intercropping	0.80
	Strip Cropping	0.60	Dense Intercropping	0.70
	Applying Mulch	0.50	Stone Cover(40%)	0.80
	Stone Cover (80%)			

Source: Hurni (1988).

Estimations of the rate of soil loss in the Highlands of Eritrea vary considerably (see Section 2.4). Apart from the fact that these figures were based on debatable assumptions, such an average estimate for the whole of highlands is far from sufficient for meaningful economic analysis. Soil loss data for various categories of soil, topography and land use and land management is important because the rate of soil loss varies considerably due to variations in the above factors.

Annual soil losses and run-off from experimental plots in Afdeyu Research Station are the only empirical data we have for the Highlands of Eritrea. Four experimental plots were established to study the effect of different soil conservation structures on soil loss and run-off. The experiments in this research station were done only on croplands with a slope of 31 percent. These empirical results, however, provide a basis to test the accuracy of the prediction of soil loss estimates using the USLE modified for the highlands of Ethiopia by Hurni (1988) and serve as a starting point to extrapolate soil loss to lands of different slope categories, different land use and land management practices.

Table 7.14 shows that the annual rate of soil loss from the experimental plots for the period 1988 to 1998 varies considerably probably due to differences in magnitude, distribution and intensity of rainfall across the years. The average annual soil loss from the control plot is 45.1 tons/ha. The establishment of stone bunds has reduced soil loss by about 80 percent. The application of level-double ditch and Fanya-juu conservation structures has reduced soil loss by more than 90 percent.

Table 7.14 Annual soil loss (t/ha) in Afdeyu catchments 1988-1998

Year	Control plot	Stone bund	Level double ditch	Level Fanya-juu
1988	108.1	37.6	23.6	20.1
1989	2.7	0.5	0	0.2
1990	8.6	1.5	0.2	0.3
1991	20.3	8.4	1.5	4.6
1992	34.2	5.7	0.7	0.9
1993	10.7	0.7	0.0	0.3
1994	6.9	0.0	0.0	0.0
1995	84.0	19.7	5.7	4.7
1996	62.6	21.9	3.3	1.9
1997	54.1	3.1	0.0	0.0
1998	62.5	2.7	1.2	1.7
Mean*	45.1	9.3 (79.4%)	3.3 (92.7%)	3.2 (93%)

* Figures in bracket are percentage reduction in soil loss.

Source: Stillhardt *et al.* (2002), ARS (unpublished reports)

We now estimate the rate of soil loss using the USLE modified for Ethiopian conditions and compare it to the actual (measured) soil loss from the experimental plots. The parameters needed for the estimation are determined based on Table 7.13 as well as climate, soil, landscape, land use and land management information of the research plots presented below (Stillhardt *et al.,* 2002).

	Parameter-values
Slope = 31%	S = 3.08
Soil type: Cambisols (red brownish colour)	K = 0.28
Slope length: 30 meters	L = 1.2
Average rainfall (11 years included in table 7.16): 473mm	R = 258
Types of crops: often cereals	C = 0.18
Management Factor: Ploughing on contour	P = 0.9

Calculated soil loss = 43.25

We can see that the actual average soil loss (45.1 tons/ha/year, see Table 7.14) is similar to the soil loss predicted by the USLE, which is 43.25. Thus it may be justified to use the USLE to estimate the rate of soil loss from different slope categories and different land uses.

Table 7.15 shows the estimated rate of soil loss from different soil types and land uses based on the parameters in the USLE in Table 7.13. We first adjust the estimated soil loss (43.3 t/ha/year) for soil types s_1, s_2 s_3 and s_4, which have an average slope of 4%, 12%, 22%, and 40%. According to the USLE (A = R*K*S*L*C*P) the estimated soil loss is (258*3.08*0.28*1.2*0.18*0.9 = 43.3). This refers to a slope of 31%. To estimate soil loss from other slope categories we replace the S factor with the appropriate parameter from Table 7.13. For example, to calculate soil loss from s_1 (which has an average slope of 4%) we replace the parameter of factor S, which was 3.08 by 0.32[42]. This gives us 4.49 t/ha/year.

Similarly we can change the land cover factor C to estimate soil loss from grasslands and woodlands. Since cereals are the major crops in the research area, the C factor used was 0.18. This is replaced by 0.05 for grassland and 0.02 for woodlands. For example, to calculate soil loss from grasslands of soil type s_4, we divide the soil loss from croplands of soil type s_4 (53.35) by 0.18 and multiply it by 0.05.

Table 7.15 Soil loss from different land categories and land use (tons/ha)

Land type (slope)	Cropland	Grassland	Woodlands
s_1 (0% - 8%)	4.49	1.24	0.50
s_2 (8% - 16%)	17.41	4.80	1.60
s_3 (16% - 30%)	34.25	9.51	3.8
s_4 (>30%)	53.35	14.81	5.92

Source: Calculated based on Table 7.13 and Table 7.14.

[42] As the parameter values for the factors are not continuous we assume a linear relationship with in each range.

Run-off

Another important benefit from the construction of stone bunds is moisture conservation. The total amount of run-off from the experimental plots in ARS is presented in Table 7.16.

Table 7.16 Rainfall and annual run-off (mm) on experimental plots (1988-1998, Afdeyu)

Year	Rainfall	Control plot	Stone bund	Level double ditch	Level Fanya-juu
1988	582.9	326.7	224.4	244.4	172.5
1989	258.8	31.9	9.5	5.0	6.6
1990	244.1	90.8	15.7	7.7	8.1
1991	320.9	150.8	78.0	23.7	63.5
1992	466.5	254.0	107.4	29.1	34.4
1993	443.9	137.8	17.6	12.2	14.3
1994	533.9	254.5	40.7	30.8	23.2
1995	658.0	248.4	148.4	108.7	106.4
1996	552.0	294.7	189.0	92.6	70.2
1997	575.0	257.3	84.6	22.0	24.7
1998	558.1	251.3	90.5	58.0	64.1
Mean (% of rainfall	472.9	208.9(44%)	91.4(19%)	57.7(12%)	53.5(11%)

Source: Stillhardt *et al.* (2002), ARS Reports.

When no soil conservation measures are undertaken, on average about 44 percent of the rainfall is lost as a surface run-off. This is reduced to 19 percent when stone bunds are applied. The amount of run-off from lands of different slope categories and land uses can be extrapolated in the same way soil losses were estimated in the previous section. This is based on the assumption that soil loss and run-off will vary in the same proportion across the various soil types and land use activities. For example, to arrive at run-off from croplands for soil type s_1, we divide the average run-off from the control plot by 3.08 (the slope factor associated with the slope of the experimental plots) and multiply it by 0.32, the slope factor associated with soil type s_1.

Table 7.17 Annual run-off from different land categories and land use (mm)

Land Type	Cropland	Grassland	Woodlands
S1	21.70	7.73	3.00
S2	83.74	23.17	9.32
S3	165.50	46.00	18.36
S4	257.70	58.00	23.20

Source: computed based on Table 7.13 and Table 7.16

Table 7.17 shows the predicted surface run-off from land of different slopes and land use when no soil conservation measures are applied. The application of soil conservation measures makes more water available for use by crops. The average run-off from the plot where stone bunds were applied has declined by

56 percent. Assuming that the run-off from all slope categories will decline at this rate with the application of stone bunds, the additional water that will be available annually for use by crops in soil types s_1, s_2, s_3, s_4 will be 12.2, 46.9, 92.7, and 144.2 mm respectively.

7.9.3 Soil conservation and crop yield

The relationship between erosion and crop yield is a very complex one. Various studies on erosion –yield relationships in the Ethiopian highlands show considerable variations. They range from a decline of 3% per annum to 0.12 % per annum (1984; Hurni, 1985; Sutcliffe, 1993; Bojo and Cassels, 1995). Most of the variation was due to the different rates of erosion used by the authors. Those studies that resulted in a lower yield decline applied a soil life cycle model developed by Stocking and Pain (1983) as the analytical framework to establish the minimum depth required for cultivation of different crops as well as the maximum depth beyond which erosion does not immediately affect soil crop cultivation. Thus, in addition to using lower rates of soil loss, soils lost from deep soils (greater than 100 cm) were considered to have no effect.

There are no studies that relate crop yield to soil erosion in Eritrea. Long-term monitoring of annual crop yield and biomass production in the Afdeyu catchments, however, provides important data which could be analysed statistically to relate soil depth to crop yield (Araya, 1999). These types of analyses were also done in Ethiopia (Hurni, 1985; Shiferaw and Holden, 1999). The variables, which affect crop yield, include soil depth, rainfall, soil type, and the crop management system practised (e.g. number of weeding, number of ploughing, crop rotation system and the use of fertilizers).

Soil erosion also affects crop yield due to its effect on the moisture available to crops. The effect of moisture conservation due to the construction of soil conservation measures on crop yield depends on climatic conditions. Thomas and Ademseged (1984:3) noted that while the moisture conservation effect of soil conservation measures may not lead to any yield difference in wet years, in dry years it could be a "difference between a crop and no crop". Others have found a negative relationship between rainfall and crop yield in the Highlands of Ethiopia, where rainfall is high (Demeke, 1998; Shiferaw and Holden, 1999). Thomas and Ademseged (1984) suggest that 25 percent yield increase due to moisture conservation from the construction of stone bunds in dry areas should be reasonable estimates.

Harvest samples have been collected for more than one decade in the Afdeyu Research Station. Variables which affect crop yield such as rainfall, soil depth, slope, and crop management system practised (e.g. number of weeding, number of ploughing and type of fertilizer applied) were available for the years 1987 to

1998[43]. This provides data on many of the relevant variables. However, with respect to fertilizer only the type of fertilizer and not the quantity applied is presented. Table 6 provides a summary of the relevant variables obtained from the harvest samples collected between 1987 and 1998. Only barley and wheat, which are the major crops in Afdeyu, had sufficient observation for statistical analysis.

A population model for the yield function may be proposed as follows:

$$Ln(Y_i) = \beta_0 + \beta_1 ln(R) + \beta_2 ln(D) + \beta_3 ln(S) + \beta_4 P + \beta_5 F + \beta_6 W + \varepsilon_I \qquad (2)$$

Where Y_i is yield of the i^{th} crop (kg/ha); R is rainfall (mm); W, P and F are dummy variables referring to crop management practices (F = 1 if fertilizer is applied, P = 1 if number of ploughing > 2, and F = 1 if fertilizer is applied); β_i are the respective partial regression coefficients; and ε_i is the population error term. It is assumed that the error term is normally distributed with a mean of zero and has a constant variance. All rainfall, soil depth, and the dummy variables included are expected to be positively related to yield.

Table 7.18 Descriptive statistics of variables from harvest sample (Barley 1987-1998)

	Rainfall (mm)	Slope (%)		Soil depth (cm)		Weeding (no)		Ploughing (no)		Yield (kg/ha)	
		Barely	Wheat	Barely	Wheat	Barely	Wheat	Barely	Wheat	Barely	Wheat
Mean	472.9	9	9	23.40	21	0.97	0.97	2.25	2.25	1958	1240
Max	582.9	45	38	42.00	41	3.00	3.00	5.00	5.00	8700	3500
Min	244.1	0	0	23.38	20	0.00	0.00	1.00	1.00	100	150

Sample size: Barley = 144 Wheat = 110
Source: Harvest sample reports of ARS.

A Cobb-Douglas yield function is estimated relating crop yield of barley to rainfall, soil depth, slope, number of weeding, number of ploughing, and application of fertilizer. All signs of the variables except slope were positive and significant. The adjusted R^2 was 0.47 showing that the variables included in the yield function explained 47 percent of the variations in yield. The coefficients of rainfall and soil depth show that, other things being equal, the yield of barley declines by 1.18 percent per one percent decline in rainfall and by 0.38 percent per one percent decline in soil depth.

The Cobb-Douglas functional form did not provide a good fit to the wheat yield function. Thus simple linear functional form is estimated. Although most variables did not have positive signs and/or were not significant, rainfall and soil depth were positive and significant. The adjusted R^2 was 0.18 showing that rainfall and soil depth together explain 18 percent of the variations in yield. The

[43] Yield data for 1992 and 1993 were missing and are therefore not included in the analysis.

overall F-test is highly significant for both barley and wheat. The results show that yield of wheat declines by 170 kg/ha per 100 mm decline in rainfall and by 29.4 kg/ha per one cm decline in soil depth. Table 7.19 shows the results of the production functions for barley and wheat.

Table 7.19 Wheat and barley production functions

Variables	Barley		Wheat	
	Coefficient	t-statistics	Coefficient	t-statistics
Constant	-1.94	-1.84*	-216.74	-0.94
Rainfall	1.18	7.13***	1.70	3.27***
Soil Depth	0.38	2.38**	29.4	2.25**
Manure	0.29	2.43**		
First weeding	0.26	1.96*		
Second weeding	0.34	1.86*		
Ploughing	0.13	2.52**		
Number of observations	144		110	
Adj- R^2	0.47		0.18	
Durban-Watson test	1.90		1.25	

* p < 0.1
* p < 0.05
* p < 0.01

Table 7.18 indicates that soils are very shallow in the Afdeyu Catchments. Considering an average soil depth of 40, 30, 20 and 10 cm for soil types s_1, s_2, s_3 and s_4 respectively, and the yield functions for barley and wheat, we estimate crop yield with and without the application of stone bunds for an average annual rainfall of 472.9 mm. As most fields in the Afdeyu Catchments are treated with stone bunds, the estimated yields better reflect yields when stone bunds are applied. Based on the soil loss and run-off for the different soil types presented in Table 7.15 and Table 7.17, and the effect of stone bunds in reducing soil loss and run-off, soil depth and amount of rain available for plants were adjusted to estimate crop yields when stone bunds are not applied. Table 7.20 shows estimated crop yields of barley and wheat when stone bunds are applied and not applied.

Table 7.20 Barley and wheat yields (kg) with and without the application of stone bunds

	Barley			Wheat		
	No Bund	Bund	% Change	No Bund	Bund	% Change
S1	1552	1602	3.22	1741	1763	1.26
S2	1264	1436	13.61	1383	1469	6.22
S3	942	1231	30.68	1005	1175	16.92
S4	598	946	58.19	617	881	42.79

Most of the variations between yields with and without the application of stone bunds are due to the effect of bunds on moisture conservation rather than the effects on soil depth. As the water conserved and made available to crops by the application of stone bunds are higher for the steeper slope land types (because initial run-off is higher), yield increases are higher for these land types.

However, these yields need to be adjusted for the area occupied by the conservation structures, which of course, are higher for the steeper slopes.

The area of land occupied by stone bunds depends on the length of bunds in each soil type and the area occupied by each bund, which is about 0.8 meters for stone bunds (John 1988). The length of bund required in each soil type has been discussed earlier (see Table 7.3). Table 7.21 shows the percentage of area occupied by stone bunds for different land types.

Table 7.21 Area occupied by stone bunds

Soil type	Distance between bunds (m)	Length of bund (km/ha)	Area occupied by bunds (%)
s_1	25.0	0.4	3.6
s_2	8.3	1.2	9.6
s_3	4.3	2.3	18.4
s_4*	4.0	2.5	20.8

* A horizontal spacing of 4 meters has been suggested as the minimum distance between bunds

7.10 Prices

As stated earlier, rural households in the Central Highlands engage in the buying and selling of crops, livestock, agricultural inputs, and other consumer goods and services. The prices of crops and livestock vary considerably from one region to the other and during different seasons in a given year. In an average year, households in the Central Highlands of Eritrea harvest their crops in October/November and consume their production with in four to six months. To cover their food needs for the rest of the year, households rely heavily on the market. The prices households receive for their products (producer prices) and the prices they pay (consumer prices) also differ due to variations in supply and demand in the different seasons of the year as well as due to the marketing costs involved. Since domestic production in an average-rainfall-year covers less than half of national demand, crop prices are highly influenced by the amount of commercial food imports and food aid.

Crop and livestock prices have increased considerably since 1998. Rising prices reflect reduced cereal supplies due to poor domestic production, border closures with Ethiopia and Sudan which have significantly reduced informal cross-border flows, and constrained capacity to import due to foreign exchange constraints. Other prices such as the price of wood, kerosene, vegetables and wages have also increased considerably since 1998. The evolution of crop and livestock prices during the last 10 years is presented in the Appendix 3 (Figure A1 and Figure A2).

The prices used in this study are average prices of the year 2002, the year we carried out our field work. The selling and buying prices for crops, livestock and fuel wood for the study villages are estimated based on the 2002 prices in the nearest town and marketing costs (which include transportation and storage costs and other costs)[44]. Since it is difficult to anticipate how the relative prices of the various prices included in the model would change under normal conditions, we use constant prices through out the planning period. The prices used in this study are presented in Table A7.

Reliable estimate of the discount rate is very difficult to obtain. We assume that the discount rate is equal to $1/(1+r)^t$, with r the interest rate and t is time. The official banks' interest rate for lending money is 12 percent and the interest rates of the two microfinance institutions[45] in the country are 14 and 16 percent. The official rate is used in this study but sensitivity test are conducted for higher rates of discount (see Section 8.6 and Figures A4 and A6 in Appendix 4).

7.11 Conclusions

In this chapter we have estimated the main parameters of the model presented in Chapter six. Particular emphasis was given to the estimation of availability of labour and labour requirement for various activities in different periods of the year; as well to the estimation of crop yield soil and loss from different land categories as a function of different types of fertilizers and soil conservation.

The USLE adapted for Ethipian conditions was used to extrapolate the limited data obtained from Afdeyu Research station to different land uses and to lands with different slopes. The estimated rates of soil loss obtained using the USLE for the similar conditions of the plots in the Afdeyu Research station were very similar to the actual rates of soil losst from the experimental plots.

The TCG developed for the highlands of Ethiopia, which are similar to the Highlands of Eritrea, was the major source of data for the yield and soil loss data. The data obtained using the TCG were compared to the limited empirical data from the country. The yields estimated using the TCG were generally higher than the yields observed in the study areas mainly due to the choice of optimal sowing date, average rainfall etc. Although we have reduced the yields to reflect the present situation, the TCG was nevertheless an invaluable source of data to obtain crop yields when different types of fertilizers and different

[44] The estimated marketing costs, defined as the difference between the farmgate price and market prices, for the three study villages are presented in Table 8.1.
[45] The two microfinance programs in Eriterea are the Southern Zone Saving and Credit Scheme and the Saving and Micro Credit Program (see Mehrteab 2005).

types of soil conservation techniques are used. As the production of empirical data for various regions and various land categories in the country is unlikely in the foreseeable future, calibrating these models by agricultural scientists for the Eritrean situation can provide a valuable source of information.

Chapter 8

Base Run and Sensitivity Analysis

8.1 Introduction

In this chapter, results of the multi-annual bio-economic model presented in Chapter six will be discussed. First, for each of the study villages the model will be run using parameter values discussed in Chapter seven. This model is called the 'base model'. Benchmark outcomes obtained from our base model – which we call the 'base results' are presented in the following section. The base results reflect land use and technology choice decisions that maximize village level net income subject to resource and subsistence constraints discussed in Chapter four. The base run model is executed for the three study villages. The results of the base model for each village are compared with current practices in that village as well as the base results of the other villages. Similarities and differences are used to explore the impacts of socio-economic, biophysical and institutional factors on farmers' decisions. The results of the base model will serve as a reference with which results of various scenarios discussed in Chapter nine will be compared. Sensitivity analysis is made for different rates of discount and different wood prices. The linear programming model is formulated in GAMS version 2.25 and solved with MINOS (see Brook *et al.,* 2003).

8.2 Results of the base model

It is reminded that the villages were selected based on their differences in population density, climate, topography, land cover and proximity to major urban centres that influence their access to off-farm employment opportunity and the transaction costs involved (see Chapter four and Table 8.1). Before presenting the results of the base model, we briefly comment on the characteristics and values presented in Table 8.1 that reflect the differences between the three villages included in this study.

Altitude and average annual rainfall of the study villages were used to estimate crop yields of the study villages (see Section 7.4.1). Access to off-farm employment, which in a number of ways affects rural household decisions, varies considerably among the study villages. Generally access to off-farm employment is higher the closer a village is to major urban centre. However, due to the border conflict and the resulting mass mobilization of able-bodied persons for military conscription, estimation of access to off-farm employment was not possible during the fieldwork. Thus the figures given in Table 8.1 are rough estimations based on subjective estimation of some respondents.

Access to additional grazing area is based on the observed practice of livestock migration to the eastern escarpments. We estimate the amount of feed requirement for livestock in each village from the seasonal migration pattern in the respective villages. In Embaderho and Maiaha livestock migrate for more than 6 months every year. However, to account for livestock that remain in the village throughout the year, it is assumed that 40 percent of livestock feed could be obtained from sources outside the village territory. The area that remains fallow is also determined based on current practice. While croplands are cultivated continuously in Zibanuna, about 25% of the croplands are assumed to remain fallow every year in Embaderho and Maiaha (see Chapter five).

Farm gate prices of crops and livestock are often much lower than consumer prices due to the costs involved in the processes of exchange. These costs, referred to transaction or marketing costs, among other things, include costs incurred by intermediaries plus their profit margin[46]. Large differences of crop and livestock prices in different cities of the country as well as seasonal price differences show the evidence of the significance of transaction costs. These costs are influenced by the distance between the village of production and the major consumption areas (the major urban centres) and the type and conditions of roads. Based on transportation costs from each village to Asmara, and price differences in Asmara and local markets nearest to the study villages, the farm gate prices of crop and livestock in Embaderho, Maiaha and Zibanuna are estimated to be 85, 65 and 75 percent of the prices in Asmara.

Table 8.1 Main characteristics of the study villages and values of parameters used in the base model

	Embaderho	Maiaha	Zibanuna
Total land per household (ha)	1.72	5.46	2.24
Average rainfall (mm/year)	540	540	600
Altitude (meters above sea level)	2400	2200	2000
Access to off-farm jobs[1]	35	0	15
Access to additional grazing[2]	40	40	0
Marketing cost[3]	0.85	0.65	0.75
Fallowing requirement	0.25	0.25	0.0

[1] percentage of the adult male population with access to off-farm employment
[2] percentage of livestock feed requirement that may be obtained from sources outside the village
[3] marketing cost is expressed as the ratio of farmgate price to the market price

[46] For a discussion of transaction costs refer to Ruijs (2002).

Benchmark outcomes were obtained for the three villages based on the characteristics described in Table 8.1 and model parameters estimated in Chapter seven (see Table A1 summary of parameters). These results will be discussed in the following sections.

Whenever possible, model outcomes are compared to current practices and similarities and differences are discussed. However, due to reasons stated below, such comparisons are not always possible. While our model is a multi-annual model, we do not have a time series of historical data with which we can compare these results. Moreover, continuous state of war has disrupted smooth economic and demographic trends in the country that current farming practices in all villages may deviate from optimal strategies. Furthermore, the base results of the model reflect choices that maximize net aggregate income of the villages. In reality, however, households with differing, and sometimes conflicting, interests are involved in these decisions (see Chapter four)[47].

The above paragraph reveals the reasons why model results could not always be compared with current practices or possible reasons for a deviation from them. In general, the results seem to describe the real situation fairly well. There are also some diverging results. These results can, however, be explained and provide interesting insights to possible improvements and policy suggestions. Converging and diverging results will be discussed below. The discussion starts with the description of simulated crop, livestock and tree-planting practices. Later we will discuss income and food availability situation in the study villages.

8.2.1 Land use

Land use decisions and the choice of technology influence rural income as well as the sustainability of land use. The decisions on land use and choice of technology are influenced by various economic, institutional and biophysical factors, which vary from one village to another in our study area. We present the base run results of allocation of land use in each village in Table 8.2 and compare the results in light of village characteristics described in Table 8.1 as well as in Chapters 5 and 7.

Cropland

The results of the base model (see Table 8.2) indicate that Embaderho has the highest area of land under crop cultivation but the lowest cropland per

[47] Results of a household level model that takes into account household level constraints and interactions among households are briefly presented for comparison purposes (Section 8.7).

household. This is to be expected given the high population density in the region. The opposite is true in Maiaha, where population density is lower (see Table 8.1) and land less suitable for cultivation (see Chapter seven).

The changes in land use over time differ among the study villages. In Maiaha the area under cultivation increases at almost the same rate as population growth throughout the planning period. Cultivated lands in Embaderho and Zibanuna, on the other hand, increase at a slower rate than population growth. The reasons of these phenomena are discussed below. On average, cultivated land in Embaderho increases at a rate of 1.3 percent per year but remains the same in Zibanuna. The evolution of simulated land use during the seven-year planning period for the three study villages is given in Figures 8.1 to 8.3.

Expansion of cropland in response to population growth may be limited due to lack of working animals, lack of land suitable for cultivation or lack of labour, if a significant proportion of the additional labour can get employment outside agriculture. In Maiaha, there is no access to off-farm employment and the needs of the rising population have to be met by agriculture. Thus, it can be well understood that cultivated land increases proportional to population growth. Lack of working animals is not an immediate constraint in Embaderho and Maiaha. The base results show that the villages maintain some cattle (cows), which may be reduced in favour of oxen, if needed for ploughing. The base results in Zibanuna, on the other hand, show that the village keeps only working animals. This is because, unlike Embaderho and Maiaha, which have access to additional grazing in the eastern escarpments, livestock in Zibanuna entirely depend on the village territory for grazing. Finally, the relatively lower population density in Maiaha leaves a relatively wider room for expansion of cultivated land. Thus while the increased demand due to population growth in Maiaha is met merely through proportional expansion of agricultural land, higher demand in Embaderho and Zibanuna is fulfilled by both expansion of land, and using more inputs per unit of land (see also Section 8.2.2), as well as engaging on off-farm activities.

Figures 8.4 to 8.6 show the simulated land use by slope category for the three study villages. Generally soils with gentle slopes are predominantly used for crop production. This is because crop yields are higher on the gentle slope land categories where soils are deeper and more water is available for plants compared to crop yields on steeper slopes where soils are shallow and considerable amount of water is lost due to run-off. However due to the shortage of sufficient land on gentle slope land categories, substantial areas of steeper slopes are cultivated both in Embaderho and Maiaha. This is also the current practice in the Central Highlands of Eritrea in general and the above-mentioned villages in particular.

Table 8.2 Some results of the base model

	Embaderho	Maiaha	Zibanuna
Land use (year 1)			
Cropland (ha)	1039	221	310
cropland (% of total)	43	21.7	39.5
cropland per household (ha)	0.74	1.15	0.93
Grassland (ha)	1139	387	453
Woodland total (ha)	214	489	8
natural woodland (ha)	0	427	0
E. plantation (ha)	214	62	8
Crop (year 1, ha)			
barley	243	44	48
millet	-	30	71
pulses	88	3	0
sorghum	257	57	47
wheat	243	43	0
taff	-	-	145
fallow	208	44	0
Livestock (year 1, head)			
oxen	537	110	172
cattle	496	243	0
donkeys	213	35	54
TLU			
Soil Conservation % (year 7)			
by land use			
cropland	25.1	29	90
grassland	0	0	2
woodlands	0	0	0
by land type			
s_1	100	-	100
s_2	25.6	62	27
s_3	0	15	46
s_4	0	0	-
Average Loss of Nitrogen (kg/ha/year)	- 21.13	-28.06	-18.9
Average Soil Loss (tons/ha/year)	11.34	13.5	4.45
Av. Soil loss from cropland tons/ha/year	17.8	24.75	9.02
Total soil loss tons/year	27010	13714	3460
Average per capita income (Nakfa)	345	330	645

Generally, the simulated choice of crops is similar to current practices in all villages. The most important crops in terms of area of land cultivated are barley, pulses, sorghum and wheat in Embaderho; barley, sorghum, millet and wheat in Maiaha; and taff, barley, millet and sorghum in Zibanuna. The simulated cultivation of sorghum, particularly in Embaderho, seems to be higher than the current practice. Farmers in Embaderho have indicated that cultivation of sorghum has considerably declined in the past years due to the decline in the early rains in March and April. When the possibility of sorghum production in Embaderho is excluded, simulated area of croplands declines substantially and becomes closer to the actual cultivated land in the village. Farmers have now to choose only between short-cycle crops and all activities have to be done at the same time. This shows that changes in rainfall patterns do not only constrain farmers' strategy of dealing with risk, but also their ability to cultivate enough land or devote sufficient labour input on the crops they cultivate.

Grazing land

Livestock graze on grazing land, fallow lands, croplands (after harvest) and on woodlands older than five years. New woodlands are restricted for grazing but grass may be collected. The simulated area of grazing lands constitutes the largest proportion of land in all the three villages: 47%, 74% and 58% percent of the total land in Embaderho, Maiaha and Zibanuna[48] (Table 8.2). This is in line with the general practice in the study villages where grazing lands cover more than 50 percent of the total land area. Maiaha has the highest proportion of grazing land because of lower population density and topography that makes most land unsuitable for cultivation. Moreover, livestock is an important component in crop production that even in Zibanuna, where land is generally more fertile, grazing area covers considerable area. The simulation results show that, when available, the steeper slope lands are used for pastures (see Figures 8.4 and 8.6).

Woodlands

The simulated areas of woodlands in the first year cover 40%, 8.9% and 1% of the total land areas in Maiaha, Embaderho and Zibanuna respectively. Although land is much more scarce in Embaderho than in Zibanuna, the simulated area of woodland is much lower in Zibanuna. By the end of the planning period, woodland areas decline to 19 percent of the total land area in Maiaha and to 6.9 percent in Embaderho. All trees are cleared in Zibanuna. There are two reasons for less area of woodlands in Zibanuna. First, land is generally more fertile in Zibanuna and the cost of tree planting in terms of forgone crop production is much higher than in the other two villages where substantial part of the land is barely suitable for crop production. Second, as stated above, while additional grazing land is available in the eastern escarpments for Maiaha and Embaderho, livestock in Zibanuna entirely depend on the village territory for grazing. Thus a larger proportion of the land has to be maintained for grazing of livestock that are vital in crop production activities.

[48] In the case of Maiaha, these include the natural woodlands established before the planning period.

Figure 8.1 Simulated land-use in Embaderho

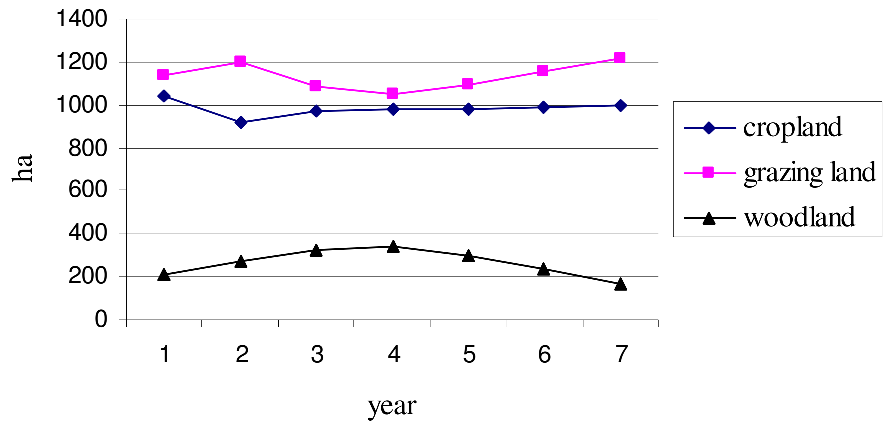


Figure 8.2 Simulated land-use in Maiaha

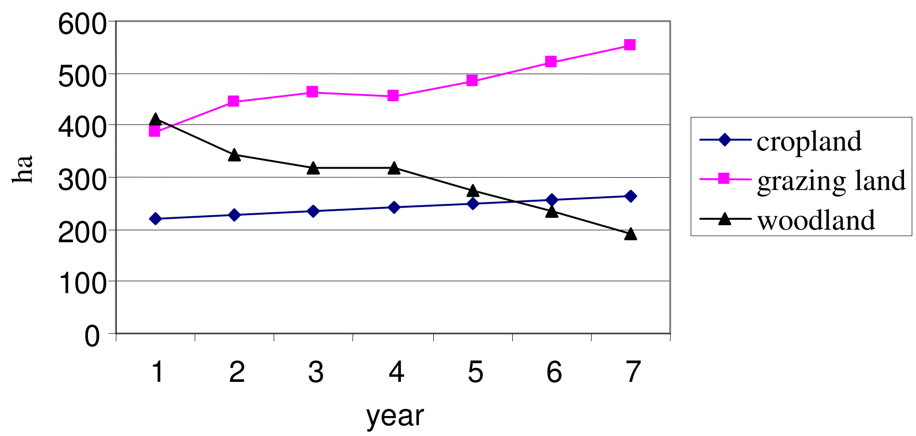


Figure 8.3 Simulated land-use in Zibanuna

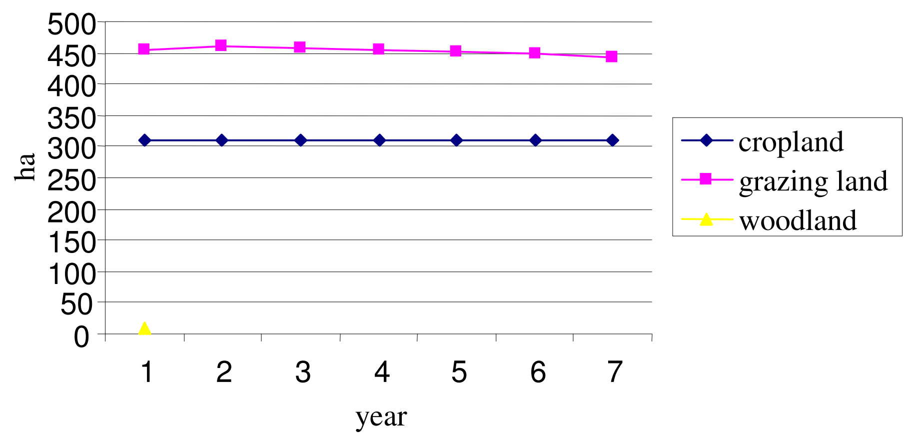


Figure 8.4 Simulated land-use by land type: Embaderho

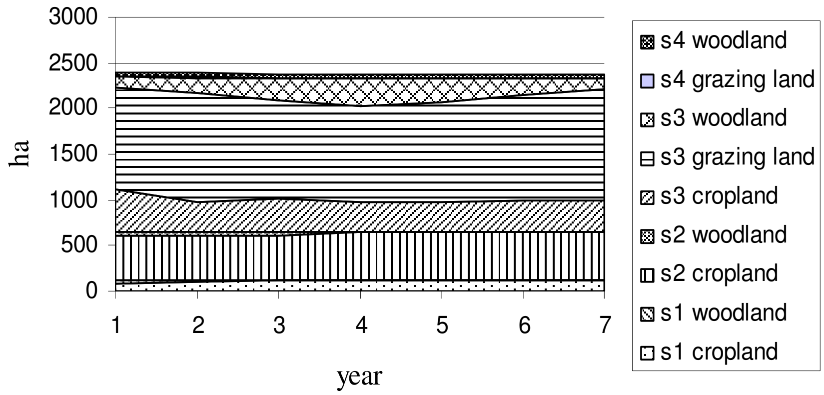


Figure 8.5 Simulated land use-by land type: Maiaha

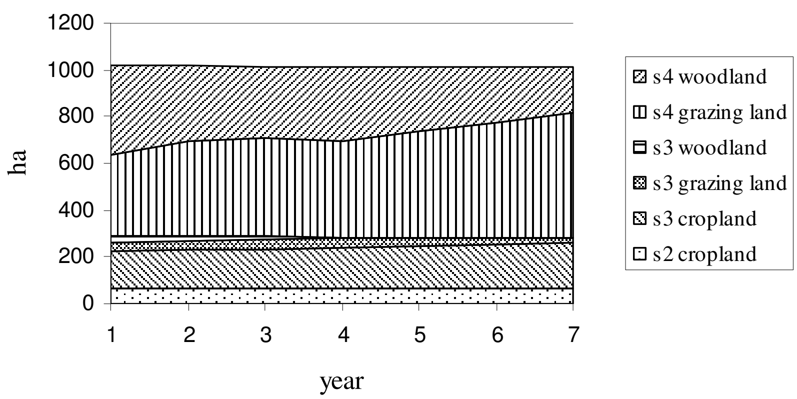
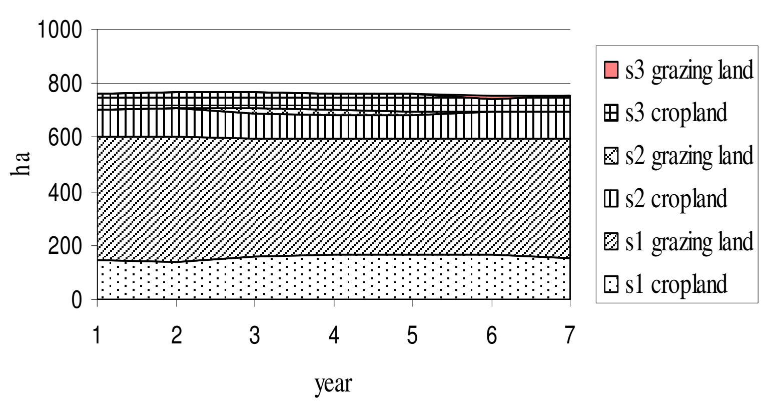


Figure 8.6 Simulated land-use by land type: Zibanuna



The base results show that new native woodlands are not established in any of the villages. This is remarkable in that natural regeneration of woodlands is suggested as a promising approach of rehabilitating the degraded woodlands in the country. Such optimism is based on the encouraging regeneration in the few permanent closures undertaken in the country as well as the lower cost of establishing them (see Section 3.3). However, no systematic evaluation has been undertaken from the view of the major stakeholders – the farmers. The results of the base model show that fast-growing eucalyptus plantations contribute more to rural income and, therefore, are more likely to be accepted. The area of native woodlands declines continuously in Maiha, the only village of the three study villages where native woodlands exist. This is partly compensated by new eucalyptus plantations.

Two key differences between model assumptions and current practices that result in differences between actual and simulated area of woodlands include:

a. The *diesa* system of communal land ownership does not allow farmers to plant trees on their croplands or any other place. Since recent years, however, in few villages degraded hillsides are parcelled out to individual households for tree planting. No such constraints are included in the base model.
b. The model assumes that wood, like crop and livestock products, can freely be produced, harvested and marketed. In reality, cutting trees from natural woodlands is strictly prohibited in Eritrea and even trees on individually owned plantations can only be cut with permission from the Ministry of Agriculture. The results of our fieldwork indicate that farmers plant trees mainly for own use.

We have conducted sensitivity tests to examine how the absence of a market or a lower price of wood affects farmers' tree planting decisions. The results are presented in Section 8.6

8.2.2 Soil conservation

As the construction of stone bunds is a labour-intensive activity it can be done only on an incremental basis every year. Thus, it is more meaningful to compare results at the end of the planning period. The extent to which stone bunds are constructed varies across the different land types in all the three villages.

Interestingly, simulation results of our base model show that stone bunds are constructed on gentle-slope lands and on croplands in contrast to the practices of the Soil and Water Conservation projects by MOA and other NGOs which focus on steep slope hillsides. This reflects the differences in objectives: while the major objective of the government and NGOs is to control land degradation, farmers build stone bunds only if it contributes to their objectives of income maximization and/or securing basic needs. The cost of undertaking soil conservation activity increases considerably with slope both in terms of labour required to construct the stone bunds and the area of land occupied by the bunds. This reduces the returns to investments on soil conservation. This fact is in conformity with current practices that farmers, although to a limited extent, build stone and soil bunds on their croplands. On the other hand, unless financed by government or NGOs, no such conservation structures are undertaken on grazing or woodland areas.

The simulated level of soil conservation also varies considerably among the study villages (Table 8.2). Relative availability (scarcity) of labour and access to off-farm employment opportunity explain the differences in construction of stone bunds among the villages. The simulated area of cropland on which stone bunds are constructed is lowest in Embaderho followed by Maiaha. This is because male labour in Embaderho and Maiaha is considerably reduced between January and May due to migration to the eastern escarpments (in search of grazing land and additional land for cultivation). Better access to off-farm jobs in Embaderho further reduces the labour available for soil conservation activities. Secondly, as discussed in Section 8.2.1, land is relatively more abundant in Maiaha that, when more labour is available (due to population growth), expanding agricultural land is more profitable than the construction of stone bunds.

8.2.3 Organic and inorganic fertilizers

Compared to actual practice, the simulated levels of fertilizer application in the Central Highlands of Eritrea is very high. All crops in Embaderho, Maiaha and Zibanuna are cultivated with the application of maximum dose considered in the model and mulching is applied on 18.5 percent of the cultivated area in Embaderho.

Despite the heavy subsidy on fertilizer, actual levels of fertilizer application are much lower than the simulated levels (see Section 5.5.3). This can be due to various factors. The literature has several explanations for low rates of adoption of innovations which can be broadly classified as sociological factors such as awareness and perception and economic factors such as access to markets, risks involved and liquidity constraints (see Section 2.5). Problems relating to fertilizer distribution and insufficient extension could be some of the factors that contribute for the low levels of fertilizer use in Eritrea. Average annual fertilizer imports in Eritrea in the period 1992-2000 were less than 5 kg per hectare of cultivated land (see Chapter two).

Low levels of fertilizer application in the Central Highlands may also be due to economic reasons, particularly risk and liquidity constraint. Since the low and erratic rainfall may significantly reduce normal absorption of nutrients by plants, the effect of fertilizer application on yield is not always guaranteed. Our field survey results show that farmers consider insufficient rainfall as the major reasons behind their low levels of fertilizer application. They believe that the application of chemical fertilizer is a risky investment due to the highly unreliable rainfall (see Section 5.5.3). Since our model is constructed for average rainfall conditions, the uncertainties caused by the high levels of rainfall variability are not taken into account. This could be an important reason for simulated levels of fertilizer application that are much higher than the actual levels.

The difference between the simulated and actual levels of fertilizer application in the study villages may also be a result of our choice of the scale of analysis. Resource constraints at a village level are not as binding as at household level. While many farmers in the study villages are too poor to afford even the highly subsidized fertilizer, this constraint is not as binding in our model as it would be in a household level model. The simulated number of oxen needed to cultivate croplands is much lower than the current number of oxen in the study villages (see Section 8.3). Thus, a large number of livestock are sold in the first year of the planning period providing the financial means to purchase chemical fertilizer and cover other expenses. The survey results, however, indicate that a large proportion of the farmers in the study villages do now own livestock. In the following section we will explain why even relatively wealthier farmers who own livestock, in practice do not want to sell their livestock to invest on fertilizer.

The base results show that manure is not applied on croplands in any of the study villages. All manure is used for fuel. In practice, as well, manure is mostly used for fuel. The results of our fieldwork show that while manure from cattle are used for fuel in all villages, manure from sheep and goats are mainly used as fertilizer.[49]

8.3 Livestock

The simulated numbers of livestock as well as the composition of livestock in the study villages differ from the livestock currently held by the villagers. The number of livestock (in TLU) ranges from 32% to 52% of the current number of livestock in the study villages. The base results indicate that oxen and donkeys

[49] In Embaderho and Zibanuna even part of the manure from sheep and goats is used as fuel.

constitute 52%, 46% and 100% of the total number of livestock in Embaderho, Maiaha and Zibanuna respectively. The proportion of oxen and donkeys in the total livestock is even higher in Embaderho and Maiaha where both types of livestock combined constitute 84% and 67% respectively.

In the first year, large numbers of livestock are sold in all the three villages resulting in a considerable difference between the simulated and actual number and composition of livestock. This is because of one or combination of the following two reasons: 1) the land cannot support current level of livestock at the suggested feed rate, 2) it is in the interest of rural households to sell livestock and purchase fertilizer, and 3) working animals (oxen and donkeys) are utilized more efficiently. We discuss these points one by one in the following paragraphs.

First, the actual level of feed consumed by livestock is lower than the suggested rate of animal feed we use in our model. In the Central Highlands of Eritrea there is an acute shortage of animal feed particularly during the dry period during which livestock are generally underfed. It is reported that livestock are let undernourished for about five to six months of the year (FAO, 1997). This is reflected in late maturity, high mortality rate and low productivity of livestock. Since grazing land is owned communally, it may be in the interest of individual households to keep as many livestock as possible resulting in overstocking of livestock over and above the carrying capacity of the land (see Chapter three).

Second, given the fertilizer-yield relationship used in this study, village income may be higher if livestock are sold and the proceeds are spent on fertilizer. The return to investment in fertilizer, however, will decrease if the possibility of lower yield (or even complete crop failure) due to uncertain rainfall is taken into account. While drought affects returns to livestock as well, the impact on livestock is likely to be lower because farmers may respond by early migration of livestock, purchase of animal feed or selling the livestock. Livestock are in fact a highly valued asset for rural households not only because they are critical inputs in crop production and/or generate considerable income but also they serve to cushion the impact of drought. Thus for farmers in the Highlands of Eritrea who, given the level of poverty, are more likely to be risk averse, keeping more livestock may be more rewarding investment than buying fertilizer.

Finally, the fact that we are using a village model means that oxen and donkeys will be fully utilized. Thus only the minimum number of working animals required for land cultivation and transport are kept. In practice however each household keeps its own animals if it can afford it. Ownership of oxen means agricultural activities, particularly sowing, can be done at the right time resulting in the best yields. This results in higher proportion of oxen and donkeys than the base results of our village model.

8.4 Soil erosion and nitrogen balance

8.4.1 Soil erosion

The average simulated amount of soil loss from croplands is 18.5, 26.5 and 7.2 tons/ha/year for Embaderho, Maiaha and Zibanuna respectively. The average soil loss from all land area of the village is 11.6, 12.4 and 3.7 tons/ha/year for the three villages respectively. Maiaha and Zibanuna have the highest and lowest level of soil erosion respectively due to the combined effect of topography and proportion of land where stone bunds are constructed (see Section 8.2). The average rate of soil loss declines substantially in Zibanuna as stone bunds are constructed on larger areas of the village land. On the other hand, soil loss in Maiaha remains very high as the benefits from the construction of stone bunds are offset as woodlands are cleared and larger proportions of the steeper land categories are brought into cultivation (see Figure 8.7).

Figure 8.7 Simulated average soil loss from croplands

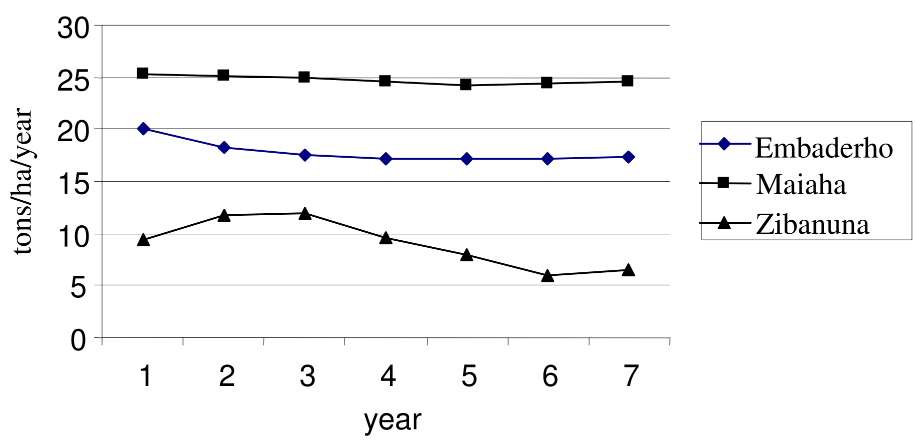
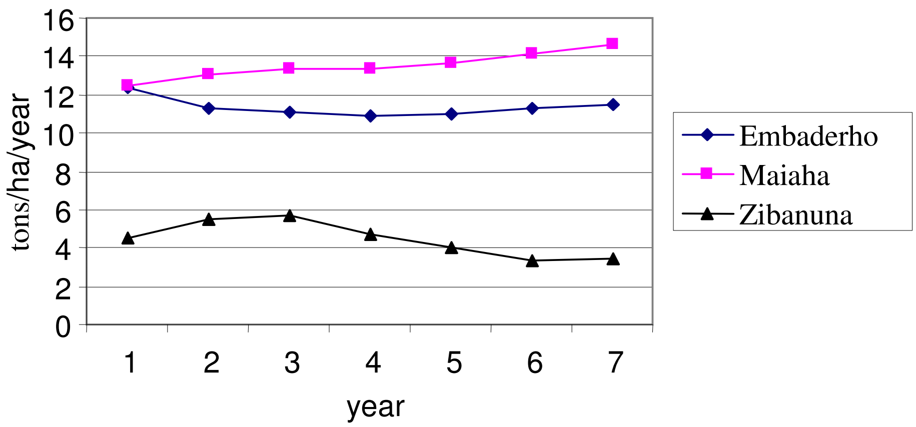


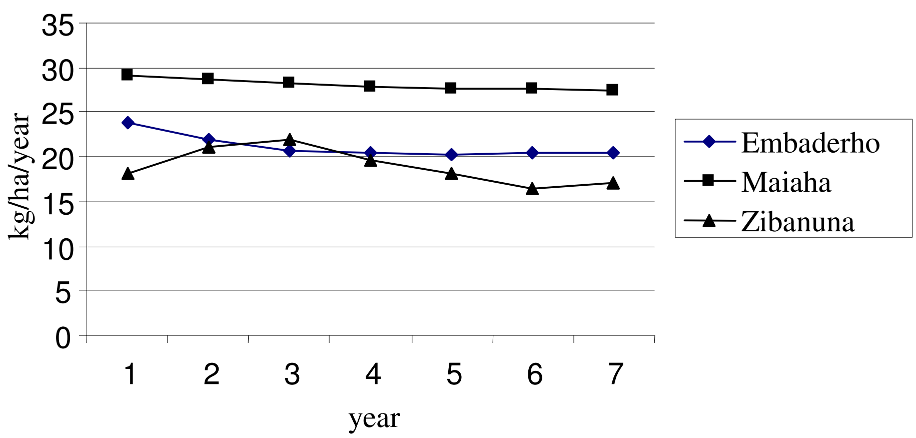
Figure 8.8 Simulated average soil loss



8.4.2 Nitrogen loss

In most cultivated soils of Eritrea, fertility has been declining, as nutrients are lost through soil erosion and removal of harvested products and crops residues without replenishment by addition of organic or chemical fertilizers. The average simulated nitrogen losses from croplands are 21.3, 28.3 and 18.3 kg per ha per year in Embaderho, Maiaha and Zibanuna respectively. Figure 8.9 shows that nitrogen loss slightly declines overtime. The differences in nitrogen losses are mainly explained by the level of soil erosion in the villages under study (Section 8.4.1). This is because the simulated level of fertilizer use is similar in all the villages.

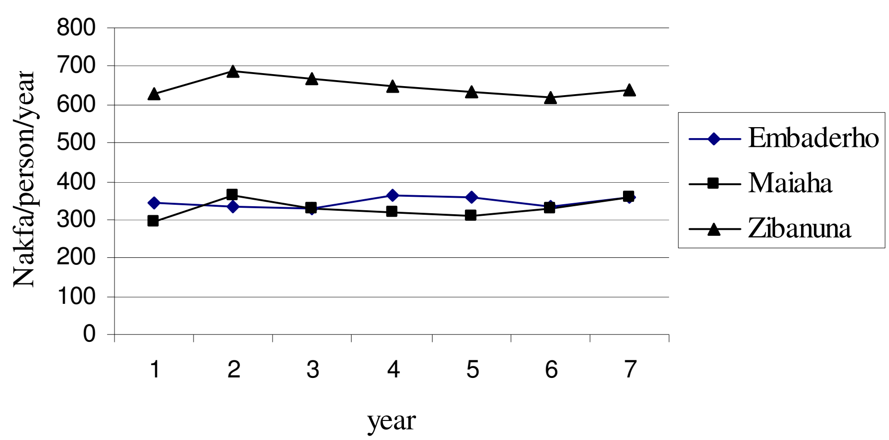
Figure 8.9 Simulated nitrogen loss from croplands



8.5 Income

The Linear programming model maximizes net income subject to the fulfilment of subsistence consumption and energy (fuel) needs. Thus the net per capita income presented here refers to what is called as the supernumerary income i.e., the income, which remains after all minimum subsistence needs are satisfied. The average per capita income, as expected, is the highest in Zibanuna, while Maiaha has the lowest level of income. All three villages have a positive net income throughout the planning period (Figure 8.8). This is not surprising for Embaderho and Zibanuna villages, where relatively higher levels of chemical fertilizers are applied. In addition, Zibanuna has relatively more fertile land and households in Embaderho have better access to off-farm jobs. The results, however, seem to be too optimistic for Maiaha. This is because, actual levels of fertilizer application are the lowest in this village and there is no access to off-farm employment opportunities.

Figure 8.10 Simulated per capita income



The base results show that two of the three villages (Maiaha and Zibanuna) produce sufficient grains and some surplus for the market. Embaderho, on the other hand, has a shortage and additional cereals are bought to fill the gap. This is mainly due to high population pressure and the resulting smaller size of land per household. These results are remarkable in that for the average rainfall and with optimal land and crop management in most areas of the Highlands of Eritrea, farmers have the potential for self sufficiency and to produce some marketable surplus. However, due to unreliable rainfall and the risks involved in investments on fertilizer, fertilizer application remains very low that farmers can only cover part of their cereal consumption from own production.

In all cases, crops with higher price are sold except a small fraction which is kept for the next year's seed requirement. Barley and sorghum, which have the lowest price, are bought for consumption. This is an obvious result that follows from our model formulation because household preferences towards different crops are not taken into account. Nevertheless, the results confirm the actual practice of farmers in the Central Highlands of Eritrea. Selling relatively expensive crops and purchasing cheaper cereals for consumption is a common strategy of rural households to cope with food shortages.

8.6 Sensitivity analysis for some parameters

The results presented in the foregoing sections of this chapter can be generalized for the parameters described in Chapter seven and in the appendices. The number of parameters is very large as can be seen in appendix 1. Doing a rigorous sensitivity analysis over all these parameters is very tedious, and in this analysis only the discount rate and the price of wood are dealt with. The rate of discount is often very difficult to estimate. However, the returns to long-term investment such as soil conservation and tree-planting and hence the decision of rural households to undertake these activities may be influenced by the choice of the discount rate. The reason we chose to conduct a sensitivity test on the price of wood is that at present farmers are not free to harvest and market wood products (see Chapter three) and it is difficult to anticipate the market price if such a ban is lifted.

As expected tree planting declines considerably both in Embaderho and Maiaha with an increase in the rate of discount and a decrease in the prices of wood[50]. Land use in both villages changes slightly with the areas of woodlands declining and grazing lands increasing. Thus the number of livestock in both villages increases. The impact on land management such as the use of fertilizers and soil conservation does not change significantly. It is interesting to note that the construction of stone bunds, which is considered as long-term investment does not change with changes in discount rate. This is due to the fact that the benefits from the construction of stone bunds begin to accrue from year one due to the importance of the moisture conserving impact.

While tree planting in Maiaha continues to decline with the decline in the selling price of wood, in Embaderho the level of tree planting ceases to decline and farmers continue to plant trees even when the selling price is very low. This is due to differences in relative availability of biomass fuels in the two villages.

[50] Sensitivity tests was not carried for Zibanuna as no trees were planted in Zibanuna in the base scenario.

Unlike in Embaderho natural woodlands, from which farmers can collect fuelwood, exist in Maiaha. The simulated number of livestock per household, and hence the supply of manure, is also higher in Maiaha (see figures in A3-A7 for the impact of discount rates and fuelwood price on tree planting in the two villages).

8.7 Household-level model

The reason for choosing a village level model as unit of analysis in this study was discussed in Chapter four. Nevertheless, the limitations that arise from aggregation have been highlighted. It has been noted that if household levels of resource endowments and constraints are not taken into account, important issues relating to food security and land management may be masked. In this section, we present the results of a household level model for Maiaha. The objective is to compare the results from the village level model and household models.

Rural households in the Central Highlands of Eritrea are generally poor and income disparities are not very noticeable. Nevertheless, some distinction of household level of income can be made depending on the ownership of key resources, particularly male-labour and livestock. Land distribution among households is egalitarian that land ownership does not account for household income disparities. However, many households lack either labour or oxen or both to cultivate their land. This opens a room for exchange of resources; however, the market for the inputs in rural areas of the Central Highlands is thin. As discussed in Chapter five, various forms of cooperation and exchange of resources take place. Households that lack labour and/or oxen may overcome this constraint(s) by a) hiring the services one or both of the resources, b) exchanging the service of one input for the other, c) ox-pairing d) renting out their land and e) relying on the assistance of relative or neighbour. A summary of these exchange processes for the three regions in the Central Highlands is presented in Table 8.3

Table 8.3 Number of households by source of labour or oxen for crop cultivation in the Central Highlands

	Labour			Oxen		
	ZM	ZDE	ZDW	ZM	ZDE	ZDW
Own Resource	59	70	61	41	56	40
Labour-labour or oxen-oxen	2	1	0	21	22	16
Hire resource for cash	5	3	4	0	0	0
Ox-Labour exchange	1	3	5	1	3	5
Rent land	8	12	16	9	11	20
Favour from relatives	6	18	0	16	17	5

Source: General Survey.

Table 8.3 shows that despite various options by which households may adjust croplands to factors such as labour and draft power, social relationships and land rental markets are the major factors adopted to adjust the different land-factor ratio among households. This is in accordance with previous observations as well (Tiquabo, 2003). The markets for the services of labour and oxen are imperfect and adjustments through buying and selling of the service of these factors is very limited. Ox pairing (traditionally known as *lfntee* literally meaning coupling) is a common practice when households own only one ox, but hiring the service of oxen for cash is not yet developed. Exchange of the service of male labour to the service of oxen is practised to a limited extent. One of the commonly cited reasons for this is the need to supervise the person using the oxen on rental basis to prevent maltreatment or overworking of animals.

Despite variations by region and type of resource, the fact that significant proportion of households in the Central Highlands depend on relatives and neighbours for the resource they lack (with nothing to pay in return) makes it difficult to build household-level model and include these non-economic interactions among households. A household-level model that is based on the assumption that all exchange of resources among households is guided by economic interest is therefore a considerable deviation from the reality

Based on the field survey in the study villages, three categories of households were identified based on the ownership of oxen and labour. We will call these households as poor, less poor and non-poor households. The initial labour and livestock endowment of each household category are given in Table 8.4. We also assume:

1. Households may borrow oxen, hire labour and/or rent land
2. If poor or less poor households do not have enough male labour or oxen to work the land they choose to cultivate, they will pay one day

service of a male person for every ox-day they rent in and a one day service of an ox for every male labour they hire[51].

3. If households choose to rent out their land, the tenant is responsible for all activities (except soil conservation) and supplies all inputs (seeds and fertilizer). The tenant and the owner of the land share output at the rate of 2:1 respectively.
4. If trees are planted in the village, all households contribute equal amount of labour and share output equally
5. Grassland is utilized communally

Table 8.4 Characteristics of the various household categories in Maiaha

	Poor	Less poor	Non-poor
Number of households	60	50	80
Number of persons	208	187	300
Number of adult males	21	29	56
Number of oxen	0	47	120
Number of cows	0	30	157
Number of donkeys	15	30	92
Number of sheep and goat	50	150	300

Source: Own survey

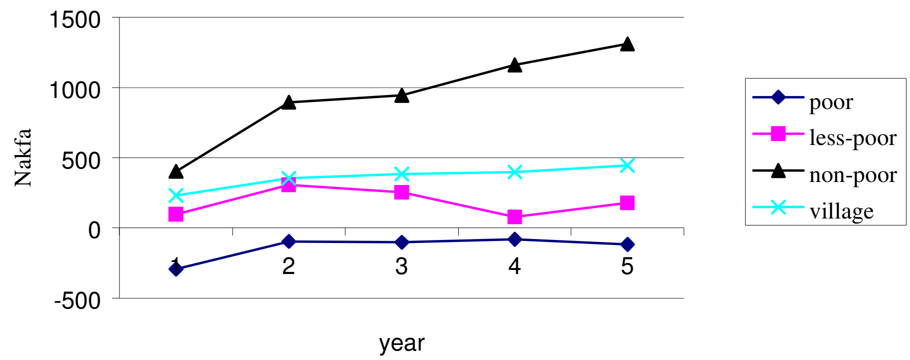
8.7.1 Results of the household model

The discounted net income used in the objective function is the weighted sum of all household categories. The weights used are proportional to the number of households in each category. Due to the low levels of endowments of labour, oxen and other livestock, the poor households are not able to meet the minimum requirements food and other subsistence needs unless some external assistance is provided. Thus food aid is introduced only for the poor households. To prevent unbounded solution and to obtain a realistic level of income that can be compared with that of other household categories, the value of food aid is deducted from the objective function.

As expected, the total discounted income of the village declines by 35 percent when a household model is used. More importantly, there is a wide gap among the incomes of the poor, less poor and non-poor households. The annual net per capita income of poor households remains negative throughout the planning period showing that this category of households is not able to produce the minimum subsistence requirements. Figure 8.11 shows the net per capita income of the three household categories from the household model and the average per capita income from the village model

[51] Exchange of resources is not only dictated by economic interest in the Central Highlands but mainly by social responsibility for those lacking the key resources for farming activities (male-labour and oxen).

Figure 8.11 Net per capita income: comparison of village and household models



The divergence between the average per capita income and the per capita income of the different household categories shows that household level analysis is crucial to understand the issues of poverty and food security problems. The differences in net per capita income among different household categories are due to a combination of factors, particularly differences in cultivated area and livestock. In addition, poor households obtain substantial amount of food aid to be able to cover subsistence needs and to purchase oxen. As discussed earlier, this is deducted from the objective function resulting in lower net per capita income for this group of households. Table 8.5 shows the simulated levels of croplands and livestock for the three categories of households.

Table 8.5 Simulated levels of cropland (ha) and livestock (head) by type of household in Maiaha

	Poor	Less-poor	Non-poor
Own cultivated land	52.9 (0.88)	40.6 (0.81)	89.5 (1.12)
Rented in land	0.0 (0.00)	0.0 (0.00)	23.6 (0.30)
Rented out land	8.8 (0.15)	14.8 (0.30)	0.0 (0.00)
Oxen	25.0 (0.41)	24.0 (0.48)	64.0 (0.80)
Donkeys	9.0 (0.15)	8.0 (0.16)	22.0 (0.27)
Cattle	0.0 (0.00)	36.0 (0.72)	309.0 (3.86)
Sheep/goats	66.0 (1.10)	198.0 (1.96)	90.0 (1.12)

* Figures in brackets represent cropland or livestock per household

The cultivated land per household (own cultivated land plus rented in land) is considerably higher for the rich household. The poor households are able to cultivate most of their cropland because with the help of the external assistance (food aid) they purchase oxen. The poor and less-poor households have generally lower number of livestock per household compared to the non-poor households. Moreover, the poor and less-poor households sell all but working animals by the third year while the livestock held by the non-poor households more than double by the end of the planning year.

Land use and land management

The simulated area of cultivated land in the household level model is slightly (7%) lower compared with the village model. We note here two factors that could have implications for the area of cultivated land. First, the fact that households with relatively more abundant resource(s) make their resources available for use by others (merely for social reasons) is not taken into account. This would probably result in larger area being cultivated by poorer households. Second, poor households are allowed to obtain food aid, which enables them to acquire oxen and cultivate more land. These two factors have offsetting influences on the cultivated land but the relative importance of each factor is not known.

The effect of using a household model on the woodlands is mixed. As stated earlier, land is communally owned in the Central Highlands and individual tree planting is possible only if community members agree to have parcels of for this activity. Thus it is assumed that all households contribute equally to tree planting and share output equally. Thus, both the establishment of new plantations and harvesting of wood from native woodlands are lower in the household model than in the village model. Consequently, while the area under woodlands at the end of the planning period is higher (less harvesting) in the village model than in the household level model, the area under eucalyptus plantations is lower (less planting) at the household model. All in all, the total area of woodlands in the village is lower in the household model than in the village model.

In both household and village level models, all croplands are cultivated with the use of either manure or chemical fertilizer. However, the proportion of cropland where manure is applied is much higher in the household model (45% in the household model compared to 23% in the village model). This is because non-poor households that own relatively larger number of livestock produce and apply more manure in the household-level model. In the village, on the other hand, all the manure belongs to the village and hence all of it is used as fuel. As we would expect, the non-poor households apply more manure while the poor and less-poor households rely more on chemical fertilizer.

The area of land where soil conservation structures are constructed is considerably lower in the household model compared to the village model (6.3 % compared to 28.9%). Interestingly, the proportion of cropland on which soil conservation structures are built is not very much different for the non-poor households who are better endowed with labour and poorer households who are less endowed with labour. This is due to the fact that the non-poor households keep more livestock and cultivate more land (renting in from other households) both of which require more labour.

8.8 Conclusions

The analysis presented in this chapter demonstrates that the village-level mathematical model developed in this study is a useful tool to explore the appropriateness of various technologies for the different regions of the study area. The model is run for three villages representing regions with different population density, market access and agricultural potential.

A comparison of model outcomes with empirical observation was also carried out. The model has fairly reproduced the allocation of land among various land uses. There were divergences between simulated and actual land management decisions such as the use of fertilizer and the construction of stone bunds. The deviations are understandable as some important conditions in the Central Highlands (for e.g. the communal ownership of land tenure, and the fact that fuel wood is not commercialized) were not explicitly taken into consideration. Moreover, while land management decisions are undertaken at the household level, for reasons discussed in Chapter four, the model developed in this study is a village level[52]. Despite some discrepancies found between model outcome and empirical data, the model can be used as a bench mark to undertake some scenario analysis in Chapter nine.

Key findings indicate that the use of inorganic fertilizer and the construction of stone bunds have positive economic returns in all the study villages. On the other hand, dung and crop residues are used for fuel and animal feed respectively. Moreover, due to high population density and the resulting expansion of cultivated land (a decline in grazing land), the number of livestock is too small to produce enough manure. The amount of manure available for use is further reduced as livestock from most parts of the study area migrate outside the village during some months of the year. Tree planting is a feasible investment most parts of the highlands except in areas of higher agricultural potential. The simulated level of tree planting is considerably higher than current practices. The *diesa* system of land tenure and the restrictions in marketing fuelwood are the major factors that result in lower levels of tree planting than is economically feasible. Sensitivity analysis shows that the choice of discount rate and a price of wood does significantly influence simulated levels of tree planting but other model outcomes are fairly insensitive to the choice of these parameters.

[52] A household model was also developed and results were compared with the village model. As the complex interactions among rural household in the Central Highlands of Eritrea are difficult to model, these model did not perform better in reproducing actual farm behaviour in the study area.

Chapter 9

Discussion of Model Results: Scenario Analysis

9.1 Introduction

Considering the biophysical and socio-economic diversity of the villages in the Central Highlands of Eritrea on the one hand, and the nature and causes of land degradation discussed in Chapter two on the other, different policy, technological and institutional strategies may be required to reduce rural poverty and control land degradation. Ehui and Pender *et al*. (1999) have suggested that different pathways are needed to escape from the downward spiral of resource degradation, low agricultural productivity and poverty in sub-Saharan Africa and that no "one-size-fits-all" approach can be successful given the enormous socio-economic and agro-ecological heterogeneity of villages and households in the region (also see Pender *et al.,* 1998; Fitsum *et al.,* 2002). A successful strategy for sustainable development in a given situation depends on the comparative advantage of a given region, which in turn depends, among other things, on agricultural potential, access to markets and population pressure.

We will use the village-level models to analyse various scenarios (see Table 9.1). The justifications for the choice of a village-level model have been discussed in Chapter four. The comparison of village and household level models in Chapter eight shows that, despite obvious limitations, the use of village level model is a useful tool of analysing land use decisions of farmers and the conditions under which various technologies may or may not be adopted. Moreover, the household model, which takes into account household level resource limitations and interactions among rural households, could not take into account resource sharing and cooperation among rural households which are not driven by economic interests.

In the following sub-sections, we will study the effectiveness of alternative technological and policy interventions for the study villages and compare outcomes in light of differences in village characteristics. We will focus on economic factors in our scenario analysis. However, the theories from the sociological models of technology adoption will also be used in explaining results.

Table 9.1 Brief description of the different scenarios

Serial number	Model scenario (Abbreviation used)	Distinguishing characteristic
1.	Base	Existing data
2.	PFERT	Removal of fertilizer subsidy: price of chemical fertilizers increased 5 times
3.	NEWSTOVE	Energy-saving stoves are introduced
4.	MECHNIZ	The possibility of hiring tractors is introduced
5.	IRRIG	Limited possibility of cultivating potatoes on irrigated land is introduced
6	FFWSC	A FFW program where farmers receive cereals for participating on the construction of stone bunds is introduced
7	FFWTP	A FFW program where farmers receive cereals for participating on tree planting activities is introduced

9.2 Scenario 1. Removal of subsidy on fertilizer (PFERT)

Fertilizer is highly subsidized in Eritrea and such high levels of subsidies cannot be sustained in the long run. It is important to explore how the removal of subsidies will influence land use decisions and investments on fertilizer and other inputs and thereby study the impact of removing fertilizer subsidy on rural income and the environment. It has been noted that efforts to improve farming systems with only little use of external inputs (termed as the low external input sustainable agriculture, LEISA) were not able to make a wide impact in developing countries (Sanders *et al*., 1996). Improved use of chemical fertilizers was therefore considered as a necessary prerequisite to poverty alleviation and circumventing land degradation in SSA. This has led to an extensive subsidy of fertilizer. Despite such higher levels of subsidy, however, the level of fertilizer use in Eritrea, as in most SSA countries, remains very low. We therefore explore how the removal of subsidies impacts on the optimal level of fertilizer use.

The price of the two major types of fertilizer used in Eritrea, Urea and DAP is Nakfa 110 (USD 7.33) and 145 (USD 9.67) per 100 kg. Although this obviously is a highly subsidized price, estimates of the level of subsidy were not available. Thus we estimate the level of subsidy by comparing the above prices to the prices in the region. The unsubsidized farm gate price of DAP in the Tigray region of Ethiopia in 1996 was USD 40.51 per 100 kg (MEDC, 1997). This shows a subsidy level of more than 76 percent. These figures are, of course, only rough estimates of the level of magnitude of subsidy because, 1) transport costs may be lower in Eritrea due to access to ports and 2) the market exchange rate in Eritrea is much higher than the official exchange rate[53].

To reflect the price of fertilizer when subsidies are removed, therefore, we consider a scenario (PFERT) in which current fertilizer prices are increased five times. The effects on income, land use, soil erosion and nitrogen balance varies considerably among the study villages. In Embaderho the model responds by reducing the cultivated land by 18.8%, but the level of fertilizer application (per hectare of cropland) remaines the same. This results in a 24 percent decline in net per capita income[54]. Surprisingly, compared to the base results, soil erosion and nitrogen loss declines under the PFERT scenario. This is due to different farmers' responses that reinforce each other's effect. With an increase in fertilizer price, the productivity of crop production relative to other activities declines leading to an increase in tree planting and livestock activities. Tree planting increases by 15 percent and grazing land expands by 12.2 percent. This led to a decline in soil loss, as soil loss from croplands is much higher than from other land use categories. In addition, since farmers cultivate less land under this scenario, more labour is available for soil conservation activities. Stone bunds are constructed on 44.6 percent of the croplands, compared to 25 percent in the base case. Finally, less of the steeper-slope land types are cultivated, leading to a decline in soil and nutrient loss.

As farmers in Maiaha entirely depend on agriculture, the effect on income is the highest. Net per capita income declines by 85 percent (or by 17% of the net full per capita income). Total cultivated area in Maiaha remains the same. However, there are some changes in land management. The proportion of cropland where chemical fertilizer is applied declines from 100% of the cultivated land in the base case to 80 percent in the PFERT scenario. Manure and crop residues (mulching) are applied on 20 percent and 6 percent of the cultivated lands respectively compared to none in the base case. In addition, stone bunds are constructed on 33.3 percent of the croplands compared to 29 percent in the base case.

Tree planting in Maiaha declines considerably under this scenario, with only 69 ha of land planted during the planning period compared to 219 ha in the base case. Grazing land, on the other hand increases substantially and the number of cattle in the village is higher by about 10 percent compared to the base case. The changes in land use and land management under this scenario have mixed effects on soil and nutrient loss. As stated above, relatively more land is treated

[53] In March 2005, the official and parallel market exchange rates were USD 1 = Nakfa 15 and USD 1 = 22.5 respectively.

[54] This refers only to the supernumerary income. The decline in full annual per capita income is only about 6.9 percent.

with soil conservation activities and all manure and some mulch are applied as fertilizer when the price of inorganic fertilizer increases. These changes reduce soil and nutrient loss. On the other hand, the declines in woodlands and in the use of inorganic fertilizer have the opposite effects. Thus soil and nutrient losses from croplands slightly decline while total soil loss increases by 6.2 percent.

In Zibanuna, the removal of fertilizer subsidies does not affect the allocation of land among different activities. However, the level of fertilizer application declines compared to the base results. More than 20 percent of the croplands are cultivated without fertilizer in the first three years under the PFERT scenario compared to none in the base scenario. As a result average soil and nutrient losses from croplands increase by 100% and 45% respectively. Total soil loss from all land increases by nearly 60 percent. Total crop production declines by 1.2 percent and net per capita income declines by 19 percent (8.2 percent of full income).

In summary we observe that higher fertilizer prices have a negative impact on income in all cases but the impact on soil erosion and nitrogen balance is mixed. In addition, the extent of the decline in income varies considerably among the study villages depending on the availability of alternative sources of income and the initial level of income. The responses to removal of subsidy are different and include, reduction in cultivated land, reduction of fertilizer application, shift to organic fertilizer and changes in the extents of soil conservation and tree planting. As a result, the impact of higher fertilizer prices on environmental indicators such as soil loss, nutrient loss and total areas of woodlands is not uniform in all the study villages

Another interesting result in this scenario is that despite a five-fold increase in the prices of fertilizer, simulated levels of fertilizer application remaines very high in all cases. While this suggests the limitation in our model arising from aggregation problem in the village model (because capital is not as binding at the village level as at household level), the results nevertheless indicate that if farmers can afford it, fertilizer is profitable even at such high levels. Consequently, policies that improve farmers' access to fertilizer such as wider distribution, extension services as well as access to credit are likely to have more impact on the adoption of this technology than subsidies.

9.3 Scenario 2. Introduction of energy saving stoves (NEWSTOVE)

As discussed in Chapter two, Eritrea is experiencing a rural energy crisis. Biomass, including wood, dung and crop residues constitutes for more than 80 percent of energy consumption in rural areas and this is primarily used in the household. The average efficiency of biomass use is very low - estimated at about 10 percent (MOE, 2000). The combination of high demand and low levels of efficiency has contributed to deforestation and aggravated rural poverty. However, the current low levels of energy use also provide an opportunity for improvement. A recent stove efficiency research found that the efficiency of wood stoves could be approximately doubled through improvements in the design of traditional stoves (EERTC, 2000).

However, the adoption of higher efficiency stoves in Eritrea may be hindered by the need of special training in the design of the new stove as well as the costs involved in acquiring it. The cash costs of improved stoves are estimated at about USD 30 or about Nakfa 450 per stove (EERTC, 2000). The new stove scenario (NEWSTOVE) requires that each household in the village buys one improved stove at the beginning of the planning period. Additional expenditures are incurred annually proportional to population growth. Per capita energy requirement when new stove are adopted is 50 percent of the energy requirements when the less efficient traditional stoves are used.

The introduction of new stoves increases net per capita income in all the three villages. All the benefits to the households in the three villages are due to less cash expenses on fuels (purchased wood and kerosene). This implies villages that depend more on the market for fuel benefit more from the use of the new energy saving stoves. As a result, the benefit from the adoption of improved stove is highest in Embaderho (Nakfa 129/person/year) followed by Zibanuna (Nakfa 103/person/year) and Maiaha (Nakfa 83/person/year). There are no changes on land use and land management decisions of the households in all the three villages.

It can be noted from the above discussion that the introduction of the new stoves is economically attractive in all cases but its contribution to the environment in the form of sustainable land use practices is not evident in all cases. We observe two key points here. The environmental benefits from the adoption of energy saving stoves were to come in the form of less wood collection (less deforestation), less burning of manure which can then be used as organic fertilizer (improving nutrient balance) and less time for the collection of fuel wood and that labour can be used for soil conservation. However, these effects are not observed in any of the study villages for the following two reasons:

First, in two of the three villages (Embaderho and Zibanuna), biomass fuels from local sources are not sufficient to meet household energy needs such that households partly depend on purchased fuels. This means that if energy requirements due to the adoption of energy saving stoves decrease, households cut on expenses on fuel; but the amounts of wood and manure used as fuel from local sources remain unaltered. In Maiaha, local biomass resources are sufficient to satisfy the present domestic energy need of all households. But when energy requirements decrease due to the adoption of energy-saving stoves, households still harvest same amount of fuel wood and increase the sales of fuel wood. Thus, energy-saving stoves ease neither deforestation nor nutrient depletion.

Second, and partly related to the above reason, the adoption of improved stoves does not save labour needed for fuel collection, as the amount of biomass used from local sources does not decrease. Moreover, while soil conservation activities are traditionally done by adult males, fuel collection is done by all males and females. Thus, even when the adoption of improved stoves saves labour needed for fuel collection, the construction of stone bunds may not necessarily increase.

The use of improved stoves could, however, have positive impacts on the environment in areas where rural households entirely depend on local biomass sources and where harvesting of fuel wood for commercial purposes is not allowed (as is the case at present). In this situation, the economic benefits and hence the adoption of the technology, are likely to be lower. But improved stoves also have other benefits, not taken into account here, like health effects and more free time and their use should be encouraged in both situations. The adoption of this technology, however, is likely to be hindered by initial financial costs and the need for training in producing the stoves. While the benefits of saving energy are realized over time, the cost of the new stove is incurred at the beginning of the planning period. As a result, net per capita income in the first year under the improved stove scenario is lower than in the base case in all the three villages. Poor farmers may not afford the initial decline in income and hence may not adopt this technology. Financial and technical assistance will be needed to encourage rural household to shift to the use of improved stoves.

9.4 Scenario 3. Mechanization (MECHNIZ)

It has been discussed that draft power is a crucial component of the farming system in the Central Highlands of Eritrea (Chapter five). However, the number of livestock in the region has declined due to the combined effects of war and drought. Large numbers of oxen were reported to have died in recent years and many farmers sold oxen and other livestock not only because they needed cash to survive the successive droughts but also because they had no feed for their livestock (FAO, 2005).

The Ministry of Agriculture provides tractor service to farmers. The tractors, which are mostly provided by bilateral donors, are made available to farmers either directly or through a farmer (contractor) who buys the tractors on credit and provide a service to the farmers. There are also some farmers who rent tractors at commercial rates. For use of these tractors MOA/Contractor charges 150 to 200 Nakfa/hr. Commercial hire is more expensive, ranging from about 250 to more than 350 Nakfa/hr. One hour is generally considered sufficient to plough half a hectare of land (FAO, 2005).

The use of tractors for land preparation instead of oxen may affect both crop yield and soil erosion. This is due to the fact that mechanization can help farmers to undertake farming activities, particularly sowing, in time. The effect of this on crop yield in areas where rainfall is a major constraint to crop production is often very significant. Moreover, the extent of disturbance of the soil differs with different tillage practices. Tillage is defined as “physical, chemical or biological manipulation of the soil to optimize conditions for germination, seedling establishment and crop growth” (FAO, 1993). Although reduced tillage is generally believed to reduce erosion, conserve moisture and increase crop yield, these effects are not considered in this study due to lack of data. Only the saving of labour and animal power is taken into account. This may affect the allocation of land and labour among different economic activities as well as the composition of livestock held by farmers, which, in turn, will affect rural income and the environment.

The use of tractors eases draft power and labour constraint at times of land preparation and sowing. However, oxen and male labour are still required for threshing. This limits the extent to which cultivated land could be extended with the introduction of tractors. Moreover, expansion of cultivated land by hiring tractor services can be economically feasible only when there exists good quality land that guarantees sufficient returns. Due to the above reasons, the level of adoption of this technology and its impact on income and the environment differ among the study villages.

The simulated cultivated lands in Embaderho and Zibanuna under the mechanization scenario are 2.5 and 6.7 percent higher respectively than the base case. Simulated cultivated land in Maiaha is the same as the base results. The proportion of land cultivated by tractor varied from 2.5 – 10 percent of total cultivated land in Embaderho and Maiaha to 33-70 percent in Zibanuna. The higher level of adoption of this technology in Zibanuna is mainly a result of the availability of good-quality land the suitability of climate and soils in the village to the cultivation of taff, a valuable cash crop that makes crop production more profitable compared to the other two villages. As a result, simulated net per capita income increases by 34 percent in Zibanuna. The increase in the other two villages is, however, very small with 3 percent in Maiaha and less than one percent in Embaderho.

Access to tractor services also affects differently the simulated soil conservation and tree planting activities of farmers in the study villages. Both total conserved area and the percentage of croplands where stone bunds are constructed increase in Zibanuna compared to Embaderho, where total conserved land increases but the percentage of land treated with stone bunds slightly declines, and to Maiaha where there is no change in soil conservation practices of the farmers. Compared to the base result, the simulated area of woodlands at the end of the planning period does not change in Maiaha and Zibanuna but are 16.4 percent higher in Embaderho. Due to the different impacts of mechanization on land use and land management, the impacts on soil loss also differ among the villages. Total amount of soil loss declines by 22.5% percent in Zibanuna and by less than 2 percent and 1 percent in Embaderho and Maiaha respectively. As there are no changes in fertilizer application in the higher mechanization scenario, there are only very small improvements in nitrogen balance resulting from a decline in soil loss in all the study villages.

9.5 Scenario 4. Irrigation (IRRIG)

It has been discussed in Chapter two that insufficient and erratic rainfall is one of the major bottlenecks for agricultural development in Eritrea. The country has no perennial rivers or streams and knowledge of availability of ground water is limited (World Bank, 1994). However, it is generally believed that the total irrigated land in the country is much lower than the potentially irrigable area. In the Central Highlands minor irrigation schemes using water from small dams or wells are practised at present. It is believed that small-scale irrigation can be expanded in this region from shallow ground water in the valleys and from the large number of micro-dams constructed before and after independence (World Bank, 1994; FAO, 2005). However, this potential is not yet fully utilized.

In terms of its environmental suitability and highly appreciated food value, potato is the main vegetable crop cultivated in the rural areas of the Highlands of Eritrea. The major potato growing zones are Maekel, Debub, Anseba and Semienawi Keih Bahri. The total area of irrigated land in the Central Highlands is estimated at about 9,000 hectares. There are about 200 micro-dams in the Central Highlands but only about 30 dams are used for irrigation. Thus most of the irrigation activities in this region depend on underground water.

As in most parts of Eritrea, there is too little surface water in the study villages to support irrigated agriculture and water from the dams in Embaderho and

Zibanuna have limited capacity that they are only used for domestic use and for watering livestock. Thus the Irrigation scenario refers to the cultivation of potatoes using pumped underground water. Digging a well and purchasing a pump are the two major initial costs required. One well and a pump are assumed to be sufficient to irrigate one ha of land and that irrigated lands will be harvested twice a year. As water is likely to be the most limiting factor in irrigation activities, it is assumed that a maximum area of 160 m^2 per household can be irrigated. Other costs include expenditures on seed, fertilizer, fuel and transport. The average yields under farmers' conditions for potatoes vary from 8 to 10 tons/ha under rain-fed conditions to 15 t/ha under irrigation (FAO, 1995).

Despite high initial costs, simulated net per capita income in the three villages increases substantially in the IRRIG scenario. The average increase in annual per capita income is Nakfa 250, 187 and 238 in Embaderho, Maiaha, and Zibanuna respectively. This difference is attributable to distance of the villages from Asmara and the resulting difference in transport costs. The increase in income is substantial considering the small size of land considered for irrigation. The results clearly show that small-scale irrigation schemes have high potential in raising rural income. However, due to high initial costs that are not affordable to the majority of rural households, and institutional constraints relating to communal land ownership, this opportunity is yet to be exploited.

The introduction of irrigation also results in changes in land use and land management practices of the farmers. Initially, the total cultivated land in Embaderho and Zibanuna under the IRRIG scenario declines substantially. However, the gap between the cultivated land in the base case and the IRRIG scenario declines over time as more labour is available with population growth. In Embaderho and Maiaha fewer trees are planted in this scenario thus the total area of woodlands are slightly lower. There is not significant change in the level of soil conservation in both Embaderho and Maiaha but due to the decline in woodlands the total level of soil loss slightly increases. Conversely, compared to the base results, more trees are planted in Zibanuna under this scenario. This is because, with a decline in the cultivated land, the number of oxen required declines making some land available for tree planting. Stone bunds are also constructed on all croplands. Due to the combined effects of higher levels of tree planting, a decline in cultivated land and higher levels of soil conservation, soil erosion declines substantially under IRRIG scenario.

9.6 Scenario 5. Food aid for soil conservation and tree planting

Food For Work programs have become increasingly popular over the past few decades not only as a means of ensuring short-term food security of the poor but also as a means of undertaking long-term investments that will enhance the productive base of the resources on which the rural poor depend for their livelihoods. Holden *et al*. (2004) identify three distinct channels through which the long-term development objectives of FFW programs can be realized. First, by relieving short-term liquidity constraints FFW programs may enable farmers to invest in soil conservation and to purchase inorganic fertilizers. Second, FFW programs can create new public goods such as roads and irrigation and soil conservation structures that can increase future productivity. Finally, FFW programs provide insurance against transitory income shocks that may force farmers to employ themselves in activities that have long-run costs such as sale of productive assets, soil and nutrient mining and excessive forest clearing.

Empirical evidence on the efficacy of FFW programs regarding the above stated contributions are limited (Barret *et al.,* 2004). However some studies show that FFW programs indeed relieve binding liquidity constraints and that the benefits associated with participation exceed the value of food received. The benefits from lower constraints are reflected either on higher investment on improved inputs or production technologies or reduced disinvestments (Bezuneh *et al.,* 1988; Barrett, 1999; Barett *et al.,* 2001).

On the contrary, FFW programs are thought to crowd out private investment. It may divert productive resources away from private activities and thereby have negative impacts on current production and long-term resource sustainability. Holden *et al*. (2004), in a survey in northern Ethiopia, found out that a considerably high proportion of farmers participating in FFW programs believed that participation gave them less time to look after their farms and animals and reduced their need to produce their own food compared to farmers who stated the opposite effects.

As discussed in Chapter eight, the base-run results show that all soil conservation activities are made on croplands. Since land types with relatively gentle slopes are generally used for crop cultivation, lands with steeper slopes and hence higher risk of soil erosion remain without any conservation. On the other hand, trees are planted on steeper slopes without the construction of stone bunds. In the following two sub-sections we explore how FFW programs for soil conservation and tree planting activities influence farmers' land use and land management decisions and thereby rural income and land degradation in the study villages.

9.6.1 Scenario 5.1 FFW for soil conservation (FFWSC)

We consider a FFW program in which farmers receive cereals for stone bunds constructed on soil types s_3 and s_4. In this scenario, 3 kg of wheat is provided per person per day for participation in FFW activities. Although men and women participate in FFW programs, traditionally only men engage in soil conservation activities on their own croplands. Thus we assume in this scenario only men can participate.

Because of the differences in village characteristics, the impact of FFW projects on land use, income and soil and nutrient loss vary among the three study villages. In Embaderho, simulated area of croplands treated with soil conservation increases from 25.1 percent in the base case to 35.6 percent and the total annual soil loss declines by 11.2 percent (from 27010 tons/ha/year in the base case to 23990 tons/ha/year). The decline is not only a result of the higher level of soil conservation but also due to changes in land use. Compared to the base case, the simulated area of cropland at the end of the planning period declines from 995 ha to 908 ha and woodlands increase from 164 ha to 275 ha. The average net per capita income in Embaderho increases only modestly from Nakfa 345 per year in the base year to Nakfa 360 per year.

Net per capita income in Maiaha increases from Nakfa 330 per year in the base scenario to Nakfa 397 under when FFW programs are introduced. The proportion of croplands where stone bunds are constructed increases slightly from 29 percent in the base case to 31.2 percent in the FFWSC scenario. As a result, soil erosion and nutrient loss from croplands decline slightly as well. However, the total amount of soil loss in the village increases from 13,714 tons/ha/year in the base scenario to 13,986 tons/ha/year. This is because the area under woodlands declines by 26 percent compared to the area under woodlands in the base scenario. Cultivated land and crop production in Maiaha remains the same as in the base scenario.

Since there is only very small area of land types s_3 or s_4 in Zibanuna, the scenario of FFW for soil conservation is not considered for this village. As discussed above, the provision of FFW for the construction of stone bunds results in higher income increase in Maiaha than in Embaderho. Two factors contribute to such a difference. First, since there is limited area of soil type s_1 or s_2 in Maiaha, even before the introduction of FFW program (in the base scenario), farmers cultivate and construct stone bunds on steeper slopes. Thus when the FFW program is introduced, they receive payments for an activity they were undertaking even without payment. In Embaderho, on the other hand, more land of type s_1 and s_2 are available. Thus in the base scenario, farmers construct stone bunds only on these land categories. The introduction of FFW induces the farmers to build stone bunds on steeper slopes, but less area of gentle-slope croplands are now treated with soil conservation structures. This offsets the benefits farmers receive in terms of FFW for the construction of stone bunds.

Second, while participation on FFW programs in Embaderho results in a decline in cultivated land, total cultivated land in Maiaha remains the same. Since farmers in Embaderho have better access to off-farm employment, participation in FFW programs comes at the expense of farm activities. Due to the decline in cultivated land, the simulated average annual crop production in Embaderho declines by 8 percent compared with the base results.

While the contribution of FFW programs for soil conservation activities is higher in Maiaha, the environmental benefits in terms of total area of woodlands, and the reducing the level of soil erosion are higher in Embaderho. Compared to the base results, total area of woodlands in Maiaha declines, proportion of cropland on which stone bunds are built increases only slightly and as a result total soil loss are higher. Conversely, When FFW programs are introduced in Embaderho, total area of woodland increases, and stone bunds are constructed on substantially higher proportion of croplands that both soil and nutrient losses decline compared to the base results.

9.6.2 Scenario 5.2 FFW for tree planting (FFWTP)

Similar to the above scenario, FFW program for tree planting in which participating farmers receive 3 kg of wheat per day is considered. Most tree planting programs in the Central Highlands of Eritrea have a primary objective of reversing on reducing land degradation and involve the construction of stone bunds, and tree planting on steep slopes. For this reason we assume that farmers receive the payments only for trees planted on steep slopes with the application of stone bunds. Trees may be harvested five years after planting and may be used for fuel or sold in the market.

Surprisingly, the total area of woodlands in Maiaha decreases by 10% compared to the base results. Stone bunds are now constructed on 30.8 percent of the woodlands; however, no stone bunds are built on croplands compared to about 30 percent in the base scenario. As a result, soil and nutrient loss from croplands as well as total level of soil loss are higher under FFWTP scenario than in the base case.

Net per capita income in Maiaha increases from 330 per year in the base case to 398 in the FFWTP scenario. However, the increase in income is much lower than the value of crops received for participating in the FFW program (net per capita income increases by Nakfa 68 per person per year while the value of crops distributed is Nakfa 262.35 per person per year). This clearly shows that participation in FFW programs is coming at the expense of other economic activities.

In Embaderho simulated area of woodlands under the FFWTP scenario increases by 35% and simulated cultivated land declines by about 13 percent compared to the base case. Stone bunds are constructed on 62.4 percent of the woodlands compared to none in the base case but no stone bunds are constructed on croplands. Total annual soil loss declines by 7.5 percent. Even average soil and nutrient losses from croplands decline slightly despite lower levels of soil conservation on croplands. This is because with a decline in the cultivated land the croplands with steeper slopes go out of cultivation.

Average annual net per capita income increases from 345 to 369. As the case with Maiaha, however, this increase is much lower than the value of food aid distributed in the program, which is Nakfa 150.60 per person per year. This is caused by the decline of cultivated land and lower yields due to less soil conservation activities.

The above results show that the way FFW programs are designed do in fact crowd out farmers' investment on their own land. However, it is important to remember that women also participate in most FFW programs and the disruption in private farming activities caused by the FFW programs may be of much lower magnitude.

Chapter 10

Summary and Conclusions

10.1 Introduction

The majority of the population in Eritrea, as in many other developing countries, depends on the agricultural sector. Increasing the productivity of this sector is, thus, vital for poverty alleviation and economic development. Moreover, the agricultural and energy sectors are the main links between the economy and the environment in the country. Declining fallow periods, expansion of cultivation into fragile steep-slopes, traditional farming practices that make little use of external inputs and high dependence on biomass fuels have contributed to high levels of land degradation and to low and declining agricultural productivity in the country. An improvement in agricultural productivity and reversing or at least reducing the environmental problems the country is facing requires the adoption of new farming methods and technologies.

Population growth and the resulting pressure on natural resources are often supposed to induce an endogenous process of agricultural intensification which takes different forms such as an increase in cropping intensity (declining fallow), the use of more labour and/or capital per unit of land, a change in the type of crop produced etc. Despite very high levels of population growth in SSA in the past several decades, however, traditional farming practices, which make little use of modern inputs, continue to dominate the region. As we have seen in Chapter two, the absence of suitable technologies as well as socio-economic, biophysical, institutional and policy conditions were blamed for the lack (or very slow process) of agricultural intensification in the region.

In Eritrea, as in many other SSA countries, land tenure and poverty are cited as major impediments to agricultural intensification and hence as the main reasons of low levels of agricultural productivity and high levels of land degradation. Communal ownership of land implies that the benefits from long-term investments on land made by a given household may not fully accrue to the same household. This is believed to have a negative impact on the willingness of rural households to make such investments on their land. Poverty is also believed to have an adverse impact on agricultural investment and resource management. The links between poverty on the one hand and agricultural intensification and land degradation on the other are, however, very complex and empirical studies give mixed results. Most case studies demonstrate a link between poverty and land degradation but few establish the direction of causality. Only very few empirical studies examine the impacts of land tenure and poverty on agricultural investment and on NRM in Eritrea.

Efforts are underway to encourage agricultural intensification in Eritrea. These include mechanization, small-scale irrigation, distribution of fertilizer and other inputs at highly subsidized prices, and soil conservation activities. Reforestation programs have also been undertaken for a long time to rehabilitate vegetative cover in the country. These include tree planting activities by mobilizing labour through Food for Work programs and student summer programs, creation of permanent and temporary closures, and distribution of free seedlings to encourage individual tree planting. New energy-saving stoves have also been developed and are being disseminated with the objectives of alleviating rural energy problems and reducing the pressure on the remaining woodlands. Despite these efforts, however, farmers' adoption of new technologies remains very low with the majority of the farmers depending on traditional farming practices.

The effectiveness of various technologies on rural income and the environment, and hence their adoption by rural households, is influenced by socio-economic, biophysical and institutional conditions. The major objectives of this study have been:

- To comprehend the rationale of land use and technology choice decisions by rural households.
- To undertake a quantitative analysis of the influence of changes in technology and governmental policies on rural income and land degradation in various regions of the Highlands of Eritrea.
- To analyse under which socio-economic and biophysical conditions new technologies are likely to be accepted.

In order to achieve the above objectives we executed a thorough study of the farming systems in the Central Highlands. These include exploring current farming practices and farmers' perceptions about the main reasons of poor agricultural performance and the major constraints to improve the system. This was done in 9 villages in different parts of the study area. More over, in-depth interviews and field studies were also conducted in selected villages representing various subregions, and discussions were carried out with community leaders and experts from various ministries. We have also developed a mathematical model that enables us to undertake a quantitative analysis of the impacts of existing or potential technologies and governmental policies on rural income and on the natural resources.

10.2 Some socio-economic and biophysical features

There are various factors which make land use and resource allocation decisions in the Central Highlands of Eritrea very complex and difficult to analyze. These include the communal land tenure system, extended family relationships among rural households, diversity of economic activities on which rural households in the study area depend for their livelihoods, and biophysical diversity among the various regions and villages in the study area.

The *diesa* system of communal land ownership is the dominant type of land tenure in the Central Highlands of the country. In this system croplands are allocated to individual households for a given period of time (usually 7 years) after which they are redistributed (see Chapter five for details on the process of distribution). During this period, rural households have an exclusive use right on their croplands only during the crop growing season. Once crops are harvested, all croplands are available for aftermath grazing by the livestock of all households in the village. Grazing lands and woodlands are used for grazing livestock and collection of wood by all members of a village.

In the *diesa* system, decisions on land use, i.e., decisions about the use of land for crop cultivation, grazing or forestry, are taken at the village level. Decisions on how to manage grazing lands and woodlands, such as when a given area of land is open for or restricted from grazing, whether and under what conditions households are allowed to cut trees etc., are also village-level decisions. On the other hand, most decisions relating to the management of the allocated croplands such as the types of crops to cultivate, the type and quantity of fertilizer to use, whether to apply soil conservation structures etc. are made at the household level. These multi-layered levels of decisions mean that neither a village nor household level analysis is sufficient to understand land use and land management decisions in the Central Highlands of the country.

Many villages in the Central Highlands are composed of households with close family ties. These family ties may lead to sharing and exchange of resources that cannot be fully explained by economic factors. Due to the communal land ownership discussed above, the size of land per household is equal for all households. However, the available amount of male labour and oxen, which are critical to crop production in the Central Highlands, vary considerably across households. Thus, while some households may be constrained by human labour, oxen or both to cultivate their croplands, others may not have enough land to employ their labour and oxen resources. This may lead to the exchange of labour for oxen, hiring labour, renting in/out of land. Such exchanges of resources, which usually take place among members of the same village, are not necessarily induced by economic benefits. It is very common that households that own neither male labour nor oxen use the resources of their close relatives to cultivate their land without offering anything in return. If there is an exchange of resources, helping the less endowed households could be a more important objective than a mutual benefit of the households participating in the transaction.

Although the Central Highlands of Eritrea cover a relatively small area of land, biophysical and socio-economic conditions vary very much. Topography, land cover, temperature and rainfall vary from one place to another. While the topography in some regions allows only a small proportion to be used for crop production, in other regions land form and soil type are more favourable for crop production. Also rainfall and temperatures may vary to some extent resulting in differences in yields. Villages in the Central Highlands also differ with respect to population density and distance from the capital city, Asmara, and other major urban centres. As a result, transportation costs and access to off-farm employment differ considerably. Hence, the profitability of various economic activities and technologies differ for the various subregions of the study area. Perspectives for the improvement of farming practices in the Central Highlands need to take these differences into account.

Farming systems in the Central Highlands of Eritrea are characterized by mixed cultivation in which rural households are engaged in both crop production and raising livestock. Due to high population pressure and small farm size, farmers from many villages in the study area seasonally migrate to the eastern escarpments and western lowlands in search of additional grazing and/or cultivable land. Moreover, rural households supplement their income from off-farm jobs in nearby towns, small-scale trade etc. This phenomenon has an important impact on the farmers' strategies of making use of available resources of land and labour.

The socio-economic and biophysical features discussed in the foregoing paragraphs have been taken into consideration in developing the mathematical model in Chapter six. However, some of the social and institutional conditions are too difficult to model. This has been carefully considered in discussing the model results.

10.3 Modelling land use and land management decisions

A village-level multi-annual bio-economic model that captures the interactions between biophysical and socio-economic factors is developed in Chapter six. The economic components of the model include crop, livestock and tree-planting activities. Crop production decisions involve choices among crop types and choice of technology, particularly the use of fertilizer, manure, mulching, and stone bunds. Livestock decisions include the number and composition of livestock. Tree-planting decisions include the type and size of land to plant with trees, the type of trees planted and the time of harvest. Farmers may also engage on off-farm jobs for a limited number of days determined by the availability of access to such jobs.

The biophysical components of the model focus on soil erosion, nitrogen loss and changes in areas of woodlands and volume of wood. Soil erosion is modelled as a function of slope, land use, and land management (use of fertilizer, and application of stone bunds). Nitrogen loss is a function of the type and quantity of fertilizer application, soil erosion and the type of crop cultivated. Area of woodlands is a function of tree planting and harvesting. The volume of wood is a function of tree planting, natural growth of trees and harvesting.

Central in this model is the interdependence of the various economic activities and the alternative uses to which resources such as manure and crop residues could be put. Crop production results in production of crop residue which is an important source of animal feed but has alternative uses such as mulching or as a source of household energy. Livestock also produces manure which can be used as fertilizer or fuel. Rural households may also purchase inorganic fertilizer, kerosene and fuelwood from the market to satisfy their demands for domestic energy and fertilizer. The allocation of resources for different end uses (such fuel, fertilizer, and animal feed) depends on the availability of the resources (which is endogenous to the model) and prices of alternatives. The major constraints in the model include:

- Labour constraints: A distinction is made between male labour and total labour. The demand for labour by all economic activities in any period of the year should not exceed the available labour in that period (adjusted for religious holidays).
- Land constraints: A distinction is made between different land types. For each land type, the total area of land allocated for crop production, grazing and forestry should not exceed the total available area of each land type adjusted for area occupied by conservation structures.
- Crop residue balance: The sum of crop residues used as fodder, fuel and fertilizer (mulching) should not exceed the residues available from crops.

- Dung balance: The available dung should at least be equal to the sum of dung used as fuel and fertilizer.
- Wood balance: The volume of wood on woodlands in any given year is the volume of wood in the previous year, plus the natural growth minus harvests during the year. Volume of wood harvested should be less than the available wood in any year.
- Cash balance: Total cash expenditure in any given year cannot exceed available cash.
- Feed balance: Total feed (dry matter) requirements of all types of livestock have to be satisfied from crop residues and grass from the grazing and woodlands.
- Energy balance: Total energy needs of all households must be met from dung, crop residues and wood used as fuel and purchased fuels.
- Food Balance: The total subsistence needs of all households must be met from own production and purchased crops.

The choice of the unit of analysis is given considerable attention. Since key decisions are made both at a village and household level, neither a village nor a household level model alone is sufficient. Due to the fact that major land use decisions have been undertaken at the village-level and the importance of non economic factors that govern resource sharing and exchange among rural households, a village-level model is selected for this study. However, this leaves out some important household-level constraints. With the village-level model we can explore the impact of various technologies and polices on aggregate income of the village, but how different groups of households will be affected cannot be known. A household-level model that incorporates poor, less-poor and non-poor households was developed for comparison purposes.

Some of the investments considered in this study, such as soil conservation and tree planting, have long-term payoffs. Thus a multi-annual model is developed. The length of the planning period is 7 years to coincide with the number of years households can cultivate a given plot before the next land redistribution in the *diesa* system.

Since the economic and biophysical conditions vary in different parts of the Central Highlands of Eritrea, different technologies and/or policies may be needed in different regions of the study area. Thus, three villages were selected based on population pressure, market access and biophysical conditions. While the structure of the model is the same, separate parameters reflecting the conditions of the respective villages were used. Parameters that were estimated separately for each village include, yields, prices, land and labour resources, access to off-farm jobs and the number of months livestock migrate during the year.

10.4 Some observation from the field studies

When we compare the farming practices in the three study villages, we observe that farmers in some villages have started to embark on the process of agricultural intensification. Farmers in Embaderho and Zibanuna, villages where population density is higher and transportation infrastructure is more developed, have a relatively higher adoption of modern technologies than farmers in Maiaha. Farming practices in the former two villages are characterized by a relatively higher use of chemical fertilizers and some use of tractor services resulting in relatively higher yields. Small-scale irrigation where vegetables are grown for the market is practised to a certain extent in these villages. Farmers in these villages also plant some trees for fuel wood and construction purposes. The adoption of the new technologies or the transition to modern farming practices taking place in these villages is, however, very limited in its magnitude due to political, institutional and economic problems. Thus, agricultural productivity remains low and land degradation continues to be a major problem.

Some changes in institutional arrangements are also taking place as a result of population pressure and consequent shortages in land and other resources such as wood. Residents of some villages in the Central Zone (where population density is the highest) have come up with some modifications to the communal land ownership system, which is reported as the major constraint for tree planting during our survey. Each household in these villages is allotted a small parcel on a hillside, on which it can plant trees and keep the parcel indefinitely. The entire group of households gets their parcels on the same hillside which is restricted from grazing. Similarly, a secure ownership to bore holes is established in many villages. A farmer who digs a well on his farmland keeps the ownership of the well even after the plot on which the well is located belongs to others in the next land redistribution.

To some extent adoption of new technologies and institutional changes that address constraints for long-term investments in Central Highlands of Eritrea is taking place in areas where there is higher population pressure, better market access and higher agricultural potential. However, even in villages with the above features, the process of agricultural intensification is slowed by lack of finance (fertilizer, irrigation), land tenure (soil conservation, tree planting), and political instability that disrupts smooth functioning of the economy in general and rural livelihoods strategies in particular.

Farmers' perceptions of the major bottlenecks to agricultural productivity and their perceptions on the effectiveness of various technologies to address those constraints have been explored. Farmers in the Central Highlands of Eritrea are generally aware of the decline in land productivity that is taking place in the study area. They believe that low and poorly distributed rainfall and shortage of labour are more important limiting factors to agricultural productivity than land degradation. They also believe a decline in fallow period and low levels of organic fertilizer to be more important causes of land degradation than soil erosion. Nevertheless, they believe most of their croplands need soil conservation structures to reduce run-off and increase the moisture available to crops.

Farmers in the study area believe that the application of fertilizer could more than double crop yields with adequate rainfall. However they are cautious in the use of fertilizer because rainfall is not reliable. They believe that the construction of stone bunds could have a substantial effect on crop yields mainly due to its moisture conservation effect. It is observed that lack of sufficient rainfall and liquidity constraints are the two major constraints for the use of inorganic fertilizer. Financial constraints for the application of inorganic fertilizer are more pronounced in villages that are less integrated into the market due to their distance from major urban centres and/or due to the fact that they produce less commercialized crops.

10.5 Land use and land management decisions: Results from the base run model

The impact of various biophysical and socio-economic conditions on farmers' decisions are explored by comparing simulated base run results of each village with actual practices in the village as well as by comparing the simulated results of the three villages. Land use decisions are influenced by biophysical conditions that determine the suitability of a given region for different economic activities (such as climate and topography) and socio-economic factors such as population density, the availability of labour and oxen and access to off-farm employment. Where population pressure is still very low and there is no access to non-farm employment opportunity, cultivated land increases rapidly in response to population growth. On the other hand, where rural households have access to off-farm employment part of the additional labour force is absorbed in the non-agricultural sector such that cultivated land increases at a slower rate than population growth. In addition if population pressure is already high, the expansion of cultivated land is limited by the need for additional grazing area for the oxen needed to bring additional land into cultivation (as is the case of Zibanuna).

Comparison of the simulated area of woodlands in the study villages shows that woodlands are more likely to be established where land is generally less suitable for agricultural production. In regions where agricultural potential is higher and where more valuable crops can grow the opportunity cost of tree planting is much higher than in other regions. The results also show that woodlands are economically feasible where population density is lower (such as Maiaha) or when there is access to grazing lands outside the village territories (such as Embaderho and Maiaha). Another interesting finding with the model is that native woodlands, where they exist, are likely to continuously decline over time, and that new ones are not likely to be established. Despite the reportedly high survival rate in temporary and permanent closures in different parts of the Central Highlands and the low labour requirements to establish native woodlands, eucalyptus plantations are more profitable from an economic point of view and, therefore, more likely to be accepted by rural households.

The results of the base model show that under average rainfall conditions and for current prices of fertilizer and crops, it is optimal to apply inorganic fertilizers for all crops and soil types in all regions. This is contrasted with low levels of fertilizer use in the Central Highlands of Eritrea highlighting the importance of economic and non-economic factors on the decision of rural households. Unreliable rainfall and the resulting uncertainty of yield response to fertilizer application are among the major factors for lower use of inorganic fertilizers. As discussed earlier, this is confirmed by our discussions with farmers during the field surveys. Liquidity constraints may also have contributed to the lower levels of fertilizer application, although this is not explicitly shown from our simulation results. The reason for this could be the choice of the village as a unit of analysis. At the village level financial and other resource constraints are not as binding as at a household level. The fact that fertilizer use is lower in regions where access to off-farm employments is lower and where cash earning from sale of agricultural output is limited also shows that liquidity constraints may be contributing to the very low level of fertilizer use. Several farmers also mentioned financial difficulties as the cause for lower use of inorganic fertilizers. Finally poor extension services and inefficient fertilizer distribution system, which often fails to make fertilizer available at the right time and place, contribute to the low levels of fertilizers in the region.

The use of manure and mulching to improve soil quality and increase the supply of nutrients is very limited in the Central Highlands of Eritrea. The results of the mathematical model show that all available manure is used for fuel and all the crop residues are used as animal feed. Given the small number of livestock per household the total amount of manure produced is limited. The amount of manure available for use is further reduced by the fact that livestock seasonally migrate for grazing outside the village territory. Thus there is limited potential to improve agricultural productivity using only organic fertilizers.

The construction of stone bunds is a labour-intensive activity and is traditionally done by men. Thus, availability of labour is the major determining factor for differences between simulated levels of soil conservation among study villages. The results show that stone bunds are less likely to be adopted in regions where population density is relatively lower, rural households have better access to off-farm jobs and/or in regions where farmers migrate seasonally in search of grazing land and additional cultivatable land.

In the optimal solution, farmers practise soil conservation on croplands and gentle slope land types. This contrasts with most SWC projects in the Central Highlands of Eritrea where the projects focus on steep-slope land types which are not suitable for crop production. As the construction of stone bunds on steep slopes needs more labour and the conservation structures occupy more land, the net benefits to farmers from soil conservation are higher on gentle-slope croplands than on the steeper ones.

In general, the simulated levels of soil conservation in all the study villages are higher than current levels. The results of our base model indicate that the construction of stone bunds produces positive economic returns even within 7 years, the period a household can cultivate the land before the next redistribution. However, most farmers are reluctant to construct stone bunds on their croplands because they do not want to see that another farmer use the benefits of their hard work.

10.6 Results of alternative technologies and interventions

The first scenario considered in this study was *removing or reducing fertilizer subsidy*. The impact of removing fertilizer subsidy on rural income was clear. Despite differences in magnitude, per capita income declines in all regions. The results of this scenario show that responses to fertilizer removal may take different forms which include, reducing fertilizer use, an increase in manure application, construction of more stone bunds, a shift from crop production to other activities (livestock, and tree planting) etc. These responses have a different impact on the environment such as soil erosion, nutrient loss and deforestation such that the net impact on the environment could be positive or negative. Another interesting observation from the results is also that even when fertilizer subsidy is completely removed the level of fertilizer application remains still high.

Scenario 2 deals with the introduction of new *energy-saving stoves*. The results of the model show that, if adopted, energy-saving stoves can have substantial impact on rural income as households' expenditure on energy declines. This impact is not as evident in regions where households do not depend on purchased energy sources. However, the welfare of rural households will improve as households will have less time to spend on fuel collection. The introduction of energy saving-stoves does not make significant contribution to the environment in most parts of the Central Highlands of Eritrea. Only in regions where natural woodlands still remain, rural households entirely depend on local biomass resources and where harvesting of wood for commercial purpose is not allowed, the adoption of energy-saving stoves seems to have a positive impact on the environment.

The *introduction of tractors* is explored in Scenario 3. The use of tractors relaxes labour and oxen power constraints at the critical sowing periods allowing the cultivation of more land. It may also improve crop yields by enabling farmers to sow their fields in time. The timeliness of sowing in the Central Highlands, where the growing season is very short, is critical for good crop growth and performance. Due to lack of data on the effect of the use of tractors on crop yields, however, only the effects on labour and oxen power requirements were taken into account. The results indicate that the impact on rural income and the level of adoption of this technology are higher in regions where agricultural potential is higher. The introduction of tractors contributes more to rural income in regions where biophysical conditions allow the cultivation of crops with higher market values and/or regions where land, which is highly suitable for crop production, needs to be left for grazing livestock. On the other hand, in regions of low agricultural potential, where most of the land is not suitable for crop production, replacing oxen power by tractor has less impact on rural income. The introduction of tractors also results in changes in land use, the levels of soil conservation and tree planting, which affect the level of soil erosion. These effects also differ from region to region. Apart from the high agricultural potential region, where simulated level of tractor use is relatively higher, the impact on total soil loss is very small.

Scenario 4 deals with *irrigation.* The introduction of irrigation results in a substantial increase in rural income in all regions. This is due to the combined effects of the cultivation of higher value crops and higher yields. Given the present prices of inputs and outputs, irrigation is economically feasible in all regions including the ones where transaction costs are relatively higher due to distance from major markets and relatively less developed transportation infrastructure. Financial constraints for initial investments (digging a well and water pumps) and lack of water are the two major problems for the development of irrigation practices. The introduction of irrigation also results in slight changes in land use. Cultivated land declines with the adoption of irrigation practices. This is due to higher demand for labour associated with irrigation. The impact on tree planting differs depending on whether labour or land has been the major constraint for tree planting. In regions where labour is the major constraint for tree planting, the introduction of irrigation results in a decline in tree planting. In regions where shortage of land is the major constraint, on the other hand, the introduction of irrigation activities results in an increase in tree planting. Land management practices such as the application of fertilizer and soil conservation activities on non-irrigated land do not change with the introduction of irrigation.

Finally, *FFW programs* in which food crops are offered to farmers in return for participation on soil conservation and/or tree planting activities are dealt with in Scenario 5. These programs may affect rural income and the environment in a number of ways. Here only diversion of labour from other economic activities is taken into account. The results of the study indicate that rural income increases but by a considerably lower amount than the value of the crops distributed for participating farmers. The impacts on rural income and the level of soil loss differ from region to region. This is because these projects interfere with rural households' agricultural activities in different ways. In regions where rural household have access to off-farm employment participation in FFW programs result in a decline in cultivated land. Moreover, although the level of soil conservation increases in all cases, stone bunds are constructed either on non-croplands or on steeper slope croplands where the return to soil conservation is lower. Thus crop production declines both due to a decline in cultivated land and lower yields resulting from less soil conservation activities by farmers on their croplands. The impact on the environment is uncertain. In some cases the introduction of FFW programs results in higher levels of soil loss because the construction of stone bunds shifts from croplands where there is higher risk of soil erosion to other land use categories where the risk of soil loss is relatively lower.

10.7 Final remarks and policy recommendations

The agricultural situation in the Central Highlands is in a desperate situation. High population pressure, very rugged topography, low and unreliable rainfall, decades of war and instability, and traditional farming practices have resulted in small farm sizes and low agricultural productivity. Consequently, the situation of most rural households is highly vulnerable, the majority of them depending on food aid and remittances for their survival.

At present, agricultural productivity in most parts of the Central Highlands is considerably lower than what biophysical conditions would allow. Traditional soil fertility practices such as fallowing, the application of manure, and crop rotation have been abandoned due to high population pressure, declining number of livestock, and climatic changes that compelled farmers to cultivate only short cycle crops. Adoption of modern farming practices is hindered by financial constraints, existing systems of land tenure and an unstable political situation that disrupted farming activities and discourage long-term investments. The long war of independence and the recent border war with Ethiopia (between 1998 and 2000) have also affected rural income and livelihoods in many ways, most importantly by its effect on the availability of male labour. Availability of male labour is a key component in crop production because, for cultural reasons, ploughing is exclusively done by men. The effect of shortage of male labour is also aggravated by religious rules, which prohibit farmers from undertaking major agricultural activities during religious holidays which amount to about 50 percent of the days in each month. This, coupled with the short rainy season, has a considerable effect on the intensity and timeliness of various farming activities with substantial adverse effect on yields.

Despite the grim agricultural situation in the Central Highlands, the results of this research show that the situation can be considerably improved if farmers adopt the technologies and farming practices the government is attempting to disseminate. On the basis of the analysis in this thesis, it is possible to formulate some recommendations on what types of changes should policy makers and development agencies focus to improve the system.

For each region in the Central Highlands, appropriate development paths need to be identified. Different technologies have different levels of economic returns in various regions and are hindered by different factors. Efforts to disseminate all technologies in all villages may be too demanding on the limited public funds and some technologies may not be accepted by rural households in some villages. Moreover, some public programs may even have unanticipated negative effects. For example, under current conditions, tree planting is not economically feasible in regions of higher agricultural potential. The introduction of tractors, on the other hand, has the highest returns on regions of high agricultural potential and high population density but very low returns in regions where population density is very low. Chemical fertilizer, stone bunds and irrigation have positive economic returns in all regions.

The *diesa* system of land tenure deters improvements in land management particularly the construction of stone bunds and tree planting. This is observed both from the differences between actual and simulated levels of tree planting and soil conservation and from our discussions during the field survey. The *diesa* system has its own advantages (equity and providing secure means of livelihoods) such that changing the system immediately and entirely may be neither practical nor desirable. Nevertheless, it is important that some improvements be made to the system. Expanding on the innovative approach of the farmers in some villages by providing long or indefinite title to parcels of a hillside for tree planting could be a solution (see Chapter three). Extending the period of redistribution of croplands may also provide farmers with higher benefits from investments on land (stone bunds) that they may be encouraged to undertake the investment even though the land may be allotted to another farmer in the next redistribution.

The introduction of some technologies requires investments that are beyond the economic capacity of farmers. Initial investments on buying agricultural machinery, water pumps and digging a well in most villages can only be done with some forms of external funding. On the other hand, farmers may be able to afford other agricultural inputs, particularly fertilizer, even when they are moderately subsidized. At the current level of subsidy for chemical fertilizers the government cannot supply a sufficient amount of fertilizer. Moreover, farmers' use of chemical fertilizers is hampered more by unreliability of rainfall and poor temporal and spatial distribution of fertilizer than by the price of fertilizer. The provision of credit services and improving fertilizer distribution can improve the level of fertilizer application. Reducing the current level of fertilizer subsidy may reduce the financial burden on the government without significantly reducing fertilizer use by farmers.

Public projects such as SWC projects and Forestry projects have to be carefully designed. Although most of the soil losses in the Central Highlands occur on croplands, at present SWC projects mainly focus on the construction of stone bunds on non-cropland hillsides. Since farmers who participate on these projects do so at the expense of their farm activities, the stone bunds on croplands decline and the total soil loss increases. As a result, farm income declines and the net economic benefits to participating farmers are much lower than the value of food aid distributed. If SWC projects were designed so that the stone bunds are constructed on croplands the benefits would be much higher and soil loss would decrease.

The choices of species and tree planting sites are very crucial in the success of forestry programs. Natural regeneration of indigenous species by restricting the use of land from crop production and grazing involves less labour and financial costs than planting fast-growing trees such as eucalyptus. However, the opportunity cost of land in terms of foregone crop and livestock production is very high in the Central Highlands that the latter has higher economic returns and has a higher chance of acceptance by rural households. Thus it is suggested that in areas of high population density and where the native woodlands have already disappeared forestry programs should focus on planting fast-growing trees. Conserving the limited native woodlands is no doubt an important environmental objective in Eritrea. This can be done in areas where population density is relatively lower and natural woodlands still exist, if the current restriction on cutting live wood is accompanied by introducing energy saving stoves, encouraging farmers to use commercial fuels and/or planting fast-growing trees for fuel and other purposes.

It is also suggested that tree planting programs focus on regions with lower agricultural potential and on hillsides that have less potential for crop production. Promoting tree planting in high agricultural potential areas or on cultivable lands is not only uneconomical from the farmers' point of view but also can have an adverse impact on the country's food production, which is already far below food requirements.

Finally, the recommendations discussed above can have the desired impact only if the political instability that has disrupted farming practices comes to an end. A return to a stable political situation and the return of young farmers to their farms is a major prerequisite to improve the agricultural conditions in the Central Highlands and the living conditions of the farmers.

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Appendix 1 Summary of the Linear Programming Model

Table A1 Summary of the Linear Programming Model

Parameter	Definition	Values	Parameter	Definition	Values
cland0(s,w)	(14)	§ 7.2	mnencont(v)	(86)	§ A6
tland0(s,w,y)	(14)	§ 7.2	wdencont(y)	(86)	§ A6
pstone(s)	(18)	§ 7.18	krencont	(86)	§ A6
yld(s,w,c,f)	(31)	§ 7.4.2	enreq	(86)	§ 7.7.2
fal	(32)	§ 8.2.	avmlbag(p,t)	(88)	§ 7.3.1
resid(c)	(37)	§ 7.4.2	avmlbal(p,t)	(88)	§ 7.3.1
crestock0(c)	(39)	§ A8	avlbag(p,t)	(88)	§ 7.3.1
popl(t)	(44)	§ 7.3	avlbal(p,t)	(88)	§ 7.3.1
calcont(c)	(44)	§A6	labcult(c,p)	(89)	§ 7.3.2
calreq	(44)	§ 7.8	labcutre (y)	(89)	§ 7.3.2
sdreq(c)	(44)	§ A8	labcons(s)	(89)	§ 7.3.2
popl0	(44)	§ 7.3	labtree(p,y)	(89)	§ 7.3.2
stock0(c)	(44)	§ A8	lablivs(p,v)	(89)	§ 7.3.2
vwtland(s,w,y,tt,t)	(52)	§ 7.7.2	mlab(p,c)	(89)	§ 7.3.2
wdyld(s,w,y)	(52)	§ 7.7.2	cash0	(92)	§ A8
vwtland0(s,w,y)	(52)	§ 7.7.2	bpricec(c,t)	(92)	§A 7
wdstock0(y)	(57)	§ A8	spricec(c,t)	(92)	§ A7
gryld(s,w)	(60)	§ 7.7.1	priceu(t)	(92)	§ A7
gryldw(s,w,y)	(60)	§ 7.7.1	priced(t)	(92)	§ A7
lvstck0(v)	(64)	§ 5.6	bpricev(v,t)	(92)	§ A7
grlvstk(v)	(64)	§ 7.6	spricev(v,t)	(92)	§ A7
feedreq(v)	(67)	§ 7.6	pricem(t)	(92)	§ A7
domcong	(67)	§ A5	bpricew(t)	(92)	§ A7
domconcr	(67)	§ A5	spricew(t)	(92)	§ A7
oxcult(p,c)	(69)	§ 7.3	pricek(t)	(92)	§ A7
oxdays(p)	(69)	§ 7.3	wage(t)	(92)	§ A7
donkday(p)	(71)	§ 7.3	remit(t)	(92)	§ 7.10
wdonkey	(71)	§ 7.3	hhexp(t)	(92)	§ 7.8.1
distf	(71)	§ 7.3	r	(92)	§ A7
Myld(v)	(74)	§ 7.6	erosc(s,w,c,f)	(98)	§ 7.9.2, A1, A2
manyld(v)	(76)	§ 7.6	erost(s,w,y)	(98)	§ 7.9.2
manstock0(v)	(78)	§ A8	ncontf(f)	(100)	§ A5
manurate(f)	(83)	§ 6.4	ncontc(c)	(100)	§ A5
residrate(f)	(83)	§ 6.4	nrain	(100)	§ 7.5.2
urearate(f)	(83)	§ 6.4	nfix	(100)	§ 7.5.2
daprate(f)	(83)	§ 6.4	nfal	(100)	§ 7.5.2
crencont(c)	(86)	§ A6	neros	(100)	§ A6

Table A1. continued

Variables	Definition	Variables	Definition
CLAND(s,w,c,f,t)	(15)	WDSTSOCK(y,t)	(57)
TLAND(s,w,y,tt,t)	(16)	GRASS(t)	(60)
TSTONE(s,p,t)	(19)	LVSTK(v,t)	(64)
CSTONE(s,p,t)	(19)	SELVSTK(v,t)	(64)
TCLAND(s,w,y,tt,p,t)	(20)	BUYLVSTK(v,t)	(64)
TPROD(c,t)	(35)	MILK(t)	(74)
CROPRES(c,t)	(37)	MANURE(v,t)	(77)
CRESFUEL(c,t)	(39)	MANFERT(v,t)	(78)
CRESFEED(c,t)	(39)	MANFUEL(v,t)	(78)
CRESFERT(c,t)	(39)	MANSTOCK(v,t)	(78)
CRESTOCK(c,t)	(39)	BUYUREA(t)	(84)
BUYCROP(c,t)	(44)	BUYDAP(t)	(84)
SELLCROP(c,t)	(44)	KEROSENE(t)	(86)
FOOD(c,t)	(44)	OFFARM(p,t)	(89)
SEED(c,t)	(44)	CASHBAL(t)	(92)
STOCK(c,t)	(44)	CREDIT(t)	(92)
WDHARV(s,w,y,t)	(52)	PAYCREDIT(t)	(92)
TVWDWDL(y,t)	(52)	INTEREST(t)	(92)
WDFUEL(y,t)	(57)	TSLOSS(t)	(98)
SELLWOOD(y,t)	(57)	NBAL (t)	(100)
BUYWOOD(y,t)	(57)		

Table A1. continued

Max $Max \sum_{t} (1/(1+r))^{t} \times NETBENEFIT(t)$ (103)

$$
\begin{aligned}
NETBENEFIT(t) = &\sum_{c} spricec(c,t) \times SELLCROP(c,t) - \sum_{c} bpricec(c,t) \times BUYCROP(c,t) \\
&+ \sum_{v} spricev(v,t) \times SELLIVSTCK(v,t) - \sum_{v} bpricev(v,t) \times BUYLIVSTCK(v,t) \\
&+ \sum_{v} spricev(v,t) \times [LVSTK(v,t) - LVSTK(v,t-1)] \\
&+ \sum_{y} spricew(y,t) \times SELLWOOD(y,t) - \sum_{y} bpricew(y,t) \times BUYWOOD(y,t) \\
&+ \sum_{y} spricew(y,t) \times [VWDWDL(y,t) - VWDWDL(y,t)] \\
&+ pricem \times MILK(t) + wage \times OFFARM(t) \\
&- priceu(t) \times BUYUREA(t) - priced(t) \times BUUDAP(t) - pricek(t) \times KEROSENE(t)
\end{aligned}
\tag{102}
$$

$$
\begin{aligned}
\sum_{y} TLAND(s,w_1,y,t,t) + \sum_{c,f} CLAND(s,w_1,c,f,t) = &\sum_{c,f} CLAND(s,w_1,c,f,t-1) \\
&+ (1-pstone(s)) \times \sum_{p} \{CSTONE(s,p,t) + TSTONE(s,p,t)\} \\
&+ \sum_{y,p} \sum_{tt=0}^{t-1} TCLAND(s,w_1,y,tt,p,t)
\end{aligned}
\tag{26}
$$

$$
\begin{aligned}
\sum_{y} TLAND(s,w_0,y,t,t) + \sum_{c,f} CLAND(s,w_0,c,f,t) = &\sum_{c,f} \mathrm{CLAND}(s,w_0,c,f,t-1) \\
&- \sum_{p} \{CSTONE(s,p,t) + TSTONE(s,p,t)\} \\
&+ \sum_{y,p} \sum_{tt=0}^{t-1} TCLAND(s,w_0,y,tt,p,t)
\end{aligned}
\tag{28}
$$

$$TLAND(s,w,y,tt,t) = TLAND(s,w,y,tt,t-1) - \sum_{p} TCLAND(s,w,y,tt,p,t) \tag{24}$$

$$TLAND(s,w,y,0,1) = tland0(s,w,y) - \sum_{p} TCLAND(s,w,y,0,p,t) \tag{25}$$

$$\sum_{p} CSTONE(s,p,t) \le \sum_{c,f} CLAND(s,w_0,c,f,t-1) \tag{21}$$

$$TSTONE(s,p,t) \le \sum_{y,tt} TCLAND(s,w_0,y,tt,p,t) \tag{22}$$

$$CLAND(s,w,c_6,f_0,t) = \sum_{c,f} \mathrm{fal} \times CLAND(s,w,c,f,t) \tag{33}$$

Table A1. continued

$$TPROD(c,t) = \sum_{s,w,f} yld(s,w,c,f,t) \times CLAND(s,w,c,f,t) \quad (36)$$

$$\begin{aligned} CRESTOCK(c, t) = {} & CRESTOCK(c, t - 1) + CROPRES(c, t) - CRESFUEL(c, t) \\ & - CRESFEED(c, t) - CRESFERT(c, t) \end{aligned} \quad (40)$$

$$CRESFERT(c,t) \leq CRESTOCK(c,t-1) \quad (42)$$

$$\sum_{c=1}^{5} calcont(c) \times FOOD(c,t) \geq calreq \times popl(t) \quad (45)$$

$$SEED(c,t) = \sum_{s,f,w} sdreq(c) \times CLAND(c,s,f,w,t) \quad (46)$$

$$\begin{aligned} STOCK(c,t) = {} & STOCK(c,t-1) + PROD(c,t) + BUYCROP(c,t) \\ & - SELLCROP(c,t) - FOOD(c,t) - SEED(c,t) \end{aligned} \quad (47)$$

$$SEED(c,t) \leq STOCK(c,t-1) + BUYCROP(c,t) \quad (49)$$

$$WDHARV(s,w,y,t) = \sum_{tt=0}^{t} \{ vwtland(s,w,y,tt,t) \times \sum_{p} TCLAND(s,w,y,tt,p,t) \} \quad (55)$$

$$TVWDWDL(y,t) = \sum_{s,w,tt} vwtland(s,w,y,tt,t) \times TLAND(s,w,y,tt,t) \quad (56)$$

$$\begin{aligned} WDSTOCK(y,t) = {} & WDSTOCK(y,t-1) + \sum_{s,w} WDHARV(s,w,y,t) \\ & + BUYWOOD(y,t) - SELLWOOD(y,t) - WDFUEL(y,t) \end{aligned} \quad (58)$$

$$\begin{aligned} GRASS(t) = {} & \sum_{s,w} gryld(s,w) \times \{CLAND(s,w,c_6,f_0,t) + CLAND(s,w,c_7,f_0,t)\} \\ & + \sum_{s,w,y,tt} gryldw(s,w,y) \times TLAND(s,w,y,tt,t)) \end{aligned} \quad (61)$$

$$\begin{aligned} LVSTK(v,t) = {} & (1 + grlvstk(v)) \times [LVSTK(v,t-1) + BUYLVSTK(v,t) \\ & - SELLVSTK(v,t)] \quad \text{for } t > 1 \end{aligned} \quad (65)$$

$$\sum_{v} feedreq(v) \times LVSTK(v,t) \leq domcong * GRASS(t) + \sum_{c} domconcr * CRESFEED(c,t) \quad (68)$$

$$\sum_{c,s,f,w} oxcult(p,c) \times CLAND(c,s,f,w,t) \leq oxdays(p) \times LIVESTOCK(v_1,t) \quad (70)$$

$$\begin{aligned} \sum_{p=12}^{18} LIVSTCK(v_3,t) \times donkday(p) \times wdonkey \geq {} & \sum_{c} CROPRES(c,t) \times distf \\ & + \sum_{c} PROD(c,t) \times wdonkey \end{aligned} \quad (72)$$

$$\sum_{p=2}^{6} LIVSTCK(v_3,t) \times donkday(p) \times wdonkey \geq MANFERT(v,t) \times distf \quad (73)$$

$$\sum_{v} myld(v) \times LVSTK(v,t) = MILK(t) \quad (75)$$

Table A1. continued

$$MANURE(v,t) = manyld(v) \times LVSTK(v,t) \tag{77}$$

$$\begin{aligned} MANSTOCK(v,t) = {} & MANSTOCK(v,t-1) + MANURE(v,t) \\ & - MANFERT(v,t) - MANFUEL(v,t) \end{aligned} \tag{79}$$

$$MANFERT(v,t) = MANSTOCK(v,t-1) + 0.5 * MANURE(v,t) \tag{81}$$

$$\sum_{v} MANFERT(v,t) = \sum_{s,w,c,f} manurate(f) \times CLAND(s,w,c,f,t)$$

$$\sum_{c} CRESFERT(c,t) = \sum_{s,w,c,f} residrate(f) \times CLAND(s,w,c,f,t)$$

$$BUYUREA(t) = \sum_{s,w,c,f} urearate(f) \times CLAND(s,w,c,f,t) \tag{85}$$

$$BUYDAP(t) = \sum_{s,w,c,f} daprate(f) \times CLAND(s,w,c,f,t)$$

$$\begin{aligned} enreq * popl(t) \le {} & \sum_{c} crencont(c) \times CRESFUEL(c,t) \\ & + \sum_{v} mnencont \times MANFUEL(v,t) \\ & + \sum_{y} wdencont(y) \times WDFUEL(y,t) \\ & + krencont \times KEROSENE(t) \end{aligned} \tag{87}$$

$$\begin{aligned} & \sum_{c,s,f,w} labcult(c,p) \times CLAND(c,s,f,w,t) \\ & + \sum_{s} (labcons(s) \times [CSTONE(s,p,t) + TSTONE(s,p,t)]) \\ & + \sum_{tt=0}^{t-1} \sum_{s,w,y} labcutr(y) \times TCLAND(s,w,y,tt,p,t) \\ & + \sum_{s,w,c,f} (labfert(p,f) \times CLAND(s,w,c,f,t) \\ & + \sum_{v} labliv(v,p) \times LIVSTK(v,t) + \sum_{s,w,y} labtree(y,p) \times TLAND(s,w,y,t,t) \\ & \le avlbal(p,t) - OFFARM(p,t) \end{aligned} \tag{90}$$

$$\sum_{c,s,f,w} mlab(p,c) \times CLAND(c,s,f,w,t) \le avmlbag(p,t) - OFFARM(p,t) \tag{91}$$

Table A1. continued

$$CASHBAL(t) = CASHBAL(t-1) + \sum_{c} spricec(c,t) \times SELLCROP(c,t)$$
$$+ \sum_{v} spricev(v,t) \times SELLLIVSTC(v,t) + \sum_{y} pricew(y,t) \times SELLWOOD(y,t)$$
$$+ \sum_{p} OFFARM(p,t) \times wage(t) + CREDIT(t) + pricem(t) \times milk(t) + remit(t)$$
$$- \sum_{c} bpirce(c,t) \times BUYCROP(c,t) - \sum_{V} bprice(v,t) \times BUYLIVSTC(v,t) \quad (93)$$
$$- \sum_{y} bpricew(y,t) \times BUYWOOD(y,t)$$
$$- pricek(t) \times KEROSENE(t) - priceu(t) * BUYUREA(t)$$
$$- priced(t) \times BUYDAP(t) - PAYCREDIT(t) - hh\exp(t) * POPL(t)$$

$CREDIT(t) = 0$ for t = T-1, T-2 (96)

$$INTEREST(t) = \sum_{\tau=t-3}^{\tau=t-1} r \times Credit(\tau) \quad (97)$$

$$TSLOSS(t) = \sum_{s,w,c,f} erosc(s,w,c,f) \times CLAND(c,s,f,w,t)$$
$$+ \sum_{s,w,y,tt} erost(s,w,y) \times TLAND(s,w,y,tt,t) \quad (99)$$

$$NBAL(t) = \left(\sum_{s,w,c,f} CLAND(s,w,c,f,t) * ncontf(f)\right) / \sum_{s,w,c,f} CLAND(s,w,c,f,t)$$
$$+ nrain + nfix + nfal$$
$$- \left(\sum_{s,w,c,f} ncontc(c) * CLAND(s,w,c,f,t)\right) / \sum_{s,w,c,f} CLAND(s,w,c,f,t) \quad (101)$$
$$-\left(\sum_{s,w,c,f} neros * erosc(s,w,c,f,t) * CLAND(s,w,c,f,t)\right) / \sum_{s,w,c,f} CLAND(s,w,c,f,t)$$

Appendx 2 Crop Yield and Soil Loss Functions for Maiaha and Zibanuna villages

Table A2. Cobb-Douglas yield functions (coefficients and t-statistics using Ordinary Least Square regression) Maiaha village

	Barley		Millet		Beans		Sorghum		Wheat	
	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat
C	3.6685***	44.67	3.8417***	12.64	3.8079***	26.12	3.3601***	26.39	3.4943***	29.23
ln (N)	0.8379***	28.73	0.4601***	2.93	0.8170***	11.04	1.1121***	37.63	0.8747***	19.42
ln (P)	0.1303***	6.45	0.0819*	2.51	0.1968***	6.56	0.0210	1.40	0.0809*	2.13
Mulch	0.0002***	12.52	0.0004***	12.23	0.0014***	15.47	0.0002**	14.37	0.0002***	11.15
Bund	0.20350***	9.63	0.4479***	10.35	0.5277***	10.54	0.1859***	8.09	0.2159***	7.95
STYPE2	-0.1947***	-4.71	-0.6337***	-3.52	0.5599***	-8.53	-0.0730	-0.76	-0.1424*	-2.11
STYPE3	-0.3912***	-12.00	-1.2553***	-8.79	-0.9824***	-11.82	-0.3718***	-4.84	-0.4391***	-10.25
STYPE4	-0.7597***	-20.10	-2.1837***	-22.64	-1.4567***	-12.12	-0.7739***	-10.52	-0.9511***	-24.36
No. observ.	144		144		144		144		144	
Adj. R^2	0.96		0.95		0.83		0.95		0.94	
D-W stat	1.40		2.12		1.85		2.07		1.46	

The dependent variable is log(yield). The first three variables are also in logarithm.
D-W Stat is the Durbin-Watson Statistics
* $P < 0.05$ ** $P < 0.01$ *** $P < 0.001$

Table A3. Cobb-Douglas yield functions (coefficients and t-statistics using Ordinary Least Square regression) Zibanuna village

	Barley		Millet		Beans		Sorghum		Taff	
	Coefficient	t-stat	Coefficient	t-stat	5.2560***	73.36	Coefficient	t-stat	Coefficient	t-stat
C	4.8513***	29.26	3.9644***	18.38	0.1066**	3.12	5.0399***	21.04	4.6784***	24.72
ln (N)	0.4871***	5.32	0.6341***	7.22	0.3523***	12.81	0.4960***	5.01	0.5212***	5.26
ln (P)	0.1701*	2.56	0.0003	0.009	0.0008***	9.18	0.1503*	2.24	0.1228	1.68
Mulch	0.0001***	12.14	0.0001***	12.67	0.2181***	5.25	0.0001***	14.59	0.0001***	11.39
Bund	0.1326***	6.45	0.2745***	8.71	-0.2861***	-7.00	0.0697**	3.35	0.1785***	7.00
STYPE2	0.0627***	3.89	-0.06808*	-2.05	-0.1908***	-4.53	0.0058	-0.29	0.0030	0.14
STYPE3	-0.0920**	-3.26	-0.1535***	-7.25	-0.7393***	-10.10	-0.4379***	-10.22	-0.1459***	-4.12
STYPE4	-1.0803***	-10.74	-0.6552***	-12.48	5.2560***	73.36	-0.7212	-16.56	-1.5310***	-13.66
No. observ.	144		144		144		144		144	
Adj. R^2	0.98		0.89		0.96		0.97		0.97	
D-W stat	1.98		2.43		1.65		1.73		2.05	

The dependent variable is log(yield). The first three variables are also in logarithm.
D-W Stat is the Durbin-Watson Statistics
* $P < 0.05$ ** $P < 0.01$ *** $P < 0.001$

Table A4. Soil loss functions (coefficients and t-statistics using Ordinary Least Square regression) Maiaha village

	Barley		Millet		Beans		Sorghum		Wheat	
	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat
C	2.9169***	42.95	2.9684***	20.10	2.3064***	34.86	3.1181***	22.87	3.0032***	40.32
ln(N)	-0.2981***	-12.39	-0.4243***	-7.97	-0.1613***	-4.73	-0.5256***	-16.62	-0.3409***	-13.57
ln(P)	-0.0052	-0.31	-0.0224	-0.81	-0.0194	-0.87	-0.0101	-0.6290	-0.0036	-0.23
Mulch	-0.0003***	-23.26	-0.0003***	-8.82	-0.0005***	-9.42	-0.0003***	-18.20	-0.0003***	-32.34
Bund	-0.4685***	-26.82	-0.5695***	-16.73	-0.5012***	-22.54	-0.5328***	-21.67	-0.4690***	-26.64
STYPE2	1.5663***	45.85	1.5815***	10.04	1.6257***	38.12	1.6259***	15.96	0.5677***	43.48
STYPE3	1.4744***	12.88	0.4195***	3.357	0.4325***	11.24	0.3957***	4.82	0.3495***	12.79
STYPE4	0.7197***	23.83	0.9221***	11.89	0.8247***	30.50	0.8288***	10.53	0.7283***	25.00
No. observ.	144		144		144		144		144	
Adj. R^2	0.98		0.97		0.96		0.97		0.98	
D-W stat	3.65		3.90		3.30		3.66		3.56	

The dependent variable is log (yield). The first three variables are also in logarithm.
D-W Stat is the Durbin-Watson Statistics
* $P < 0.05$ ** $P < 0.01$ *** $P < 0.001$

Table A5. Soil loss function (coefficients and t-statistics using Ordinary Least Squares regression) Zibanuna village

	Barley		Millet		Beans		Sorghum		Wheat	
	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat
C	3.1551***	57.74	3.1422***	34.78	2.6569***	132.49	1.3436***	4.02	3.1372***	57.46
ln(N)	-0.1799***	-7.19	-0.3608***	-9.81	-0.0104	-1.1983	-0.5000***	-4.39	-0.1845***	-7.51
ln(P)	-0.0648***	-3.81	-0.0065	-0.43	-0.0844***	-9.66	-0.5494	-11.87	-0.0638	-3.98
Mulch	-0.0003***	-48.72	-0.0003***	-45.72	-0.0003***	-9.31	-0.0004***	-9.39	-0.0003***	-57.74
Bund	-0.6670***	-59.05	-0.5735***	-43.47	-0.6733***	-49.67	-0.5392***	-6.31	-0.6613***	-58.73
STYPE2	0.6072***	39.47	0.6130***	44.19	0.5858***	28.60	0.3165***	3.30	0.6047***	40.18
STYPE3	1.4757***	89.91	1.4905***	42.27	1.4969***	68.70	1.5380***	43.15	1.4761***	90.52
STYPE4	1.5818***	0.4668	1.7351***	30.93	1.5295***	45.91	1.7626***	30.38	1.5604***	46.60
No. observ.	144		144		144		144		144	
Adj. R^2	0.99		0.99		0.99		0.78		0.99	
D-W stat	3.22		3.10		1.90		0.87		3.17	

The dependent variable is log (soil loss). The first three variables are also in logarithm.
D-W Stat is the Durbin-Watson Statistics
* $P < 0.05$ ** $P < 0.01$ *** $P < 0.001$

Appendix 3 Nutrient and Energy Related Data, Prices and Initial Values of Some Parameters

Table A6. Nutrients and Energy-related data*

Items	Plant nutrients (kg/ton)			Energy content of crops (kcal/kg)	Yield of crop residues (kg/kg of crop)	Feed nutrients (ton DM /ton of residues)	Primary energy (mj/kg)	Cooking efficiency (%)
	N	P	K					
UREA	460	0	0	-	-	-	-	-
DAP	190	460	0	-	-	-	-	-
Fuelwood	-	-	-	-	-	-	16.6	8
Dung	15	7.5	10	-	-	-	8.4	9
Crop and residues								
Barley	22.1	7.6		3540	1.2	0.5	12.5	8
Millet	30.7	10.1		3780	1.2	0.5	12.5	8
Pulses	29.2	17.5		3690	0.8	0.5	12.5	8
Sorghum	25.5	11.1		3390	1.2	0.5	12.5	8
Wheat	28.7	13.9		3540	1.0	0.5	12.5	8
Taff	28.7	13.9		3390	1.0	0.5	12.5	8
Kerosene	_	-	-	-	-	-	43.19	42
grass	-	-	-	-	-	0.3	-	-

* It is assumed that 1 kg of N is lost for every ton of soil loss (Smaling 1990).

Source: FAO, 1997; Newcombe, 1989; MOEM, 2000; Hanao, 1999

Table A7. Buying and selling prices used in the model

	Embaderho		Zibanuna		Maiaha	
	Buying	Selling	Buying	Selling	Buying	Selling
Crops (100 kg)						
Barley	315	255	315	225	330	195
Millet	704	570	704	503	737	436
Pulses	630	510	630	450	660	390
Sorghum	315	255	315	225	330	195
Wheat	473	383	473	338	495	293
Taff	1155	935	1155	825	1210	715
Livestock (unit)	0	0	0	0	0	0
Oxen	3150	2550	3150	2250	3300	1950
Cattle	2625	2125	2625	1875	2750	1625
Donkeys	840	680	840	600	880	520
Sheep/Goat	420	340	420	300	440	260
	315	255	315	225	330	195
Fuelwood (100 kg)	840	680	840	60	880	520
Kerosene (litre)	4.25		4.25		4.25	
Milk (litre)	2.5		2.5		2.5	
Wage (person/day)	40		40		40	

Source: Based on market prices in 2002 and marketing costs discussed in Chapter eight.

Table A8 Initial values of some parameters

	Embaderho	Maiaha	Zibanuna
stock0(c) (kg)	84000	11400	16200
crestock0(c) (kg)	840	114	162
wdstock0(c) (kg)	0	0	0
manstock0(v) (g)	30,20,10,50	30,20,10,50	30,20,10,0
cash0 (Nakfa)	0	0	0
sdreq(c) (kg)	150, 50, 50, 50, 150, 50 for barley, millet, pulses, sorghum, wheat and taff respectively.		

Fig A1. Prices of cereals and pulses in Asmara (Nakfa/100kg)

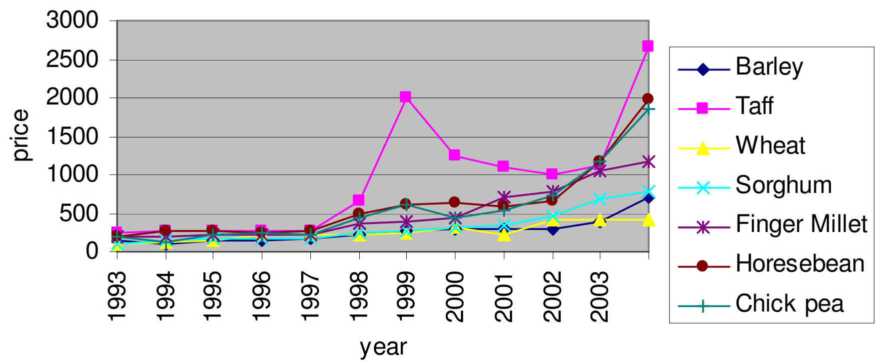
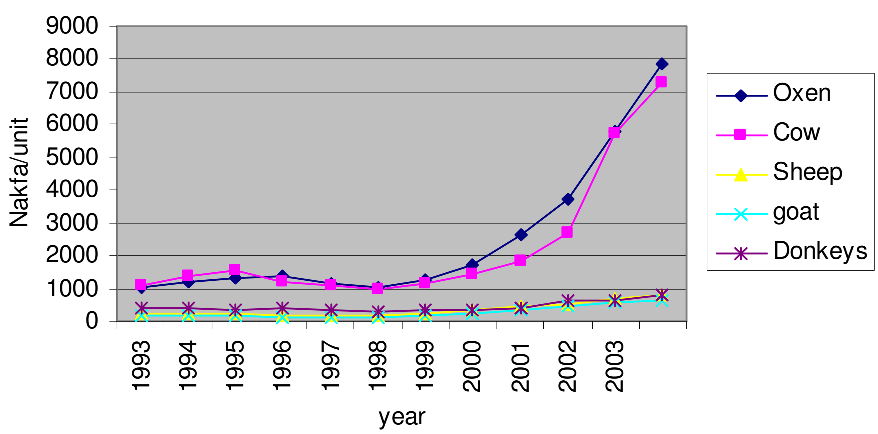


Figure A2. Evolution of livestock prices 1993-2003



Appendix 4 Results of Sensitivity Tests on Fuelwood Prices and Discount Rates

Figure A3. Simulated areas of eucalyptus plantations under different wood prices in Embaderho

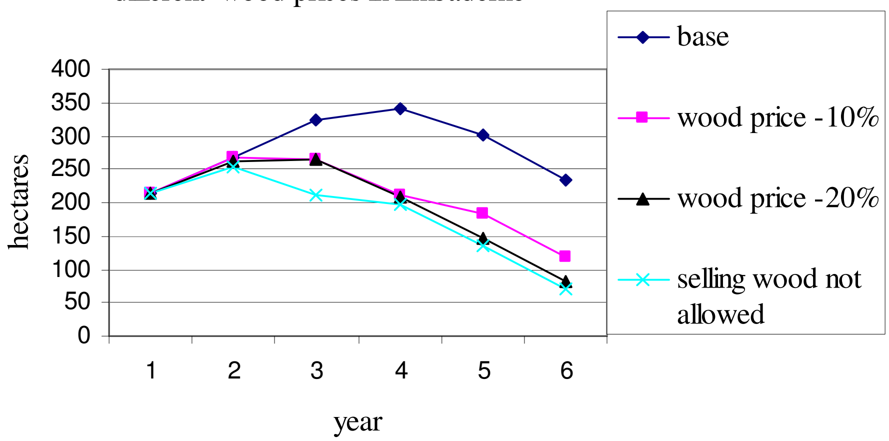


Figure A4. Simulated areas of eucalyptus plantations under different rates of discount in Embaderho

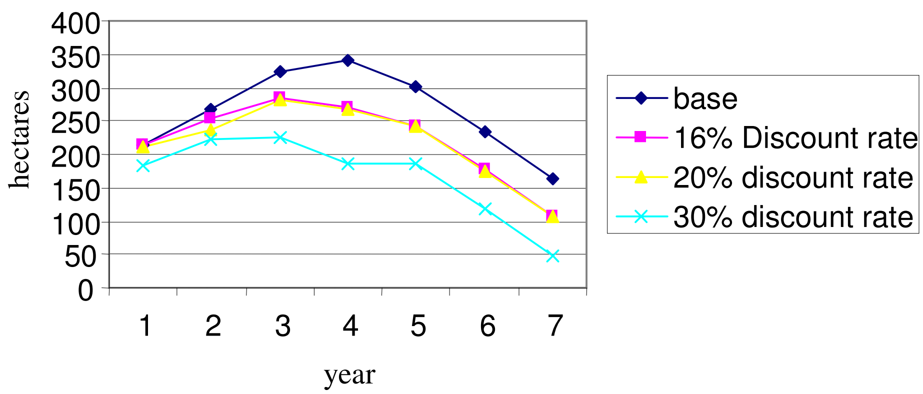


Figure A5 Simulated areas of eucalyptus plantations under different wood prices in Maiaha

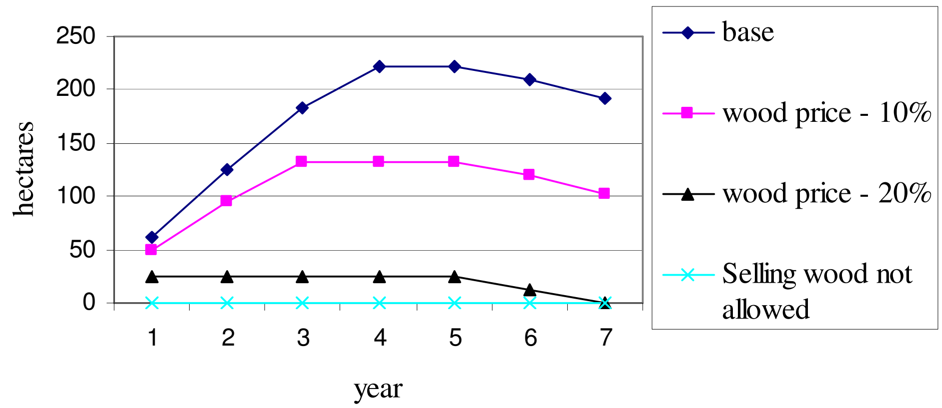
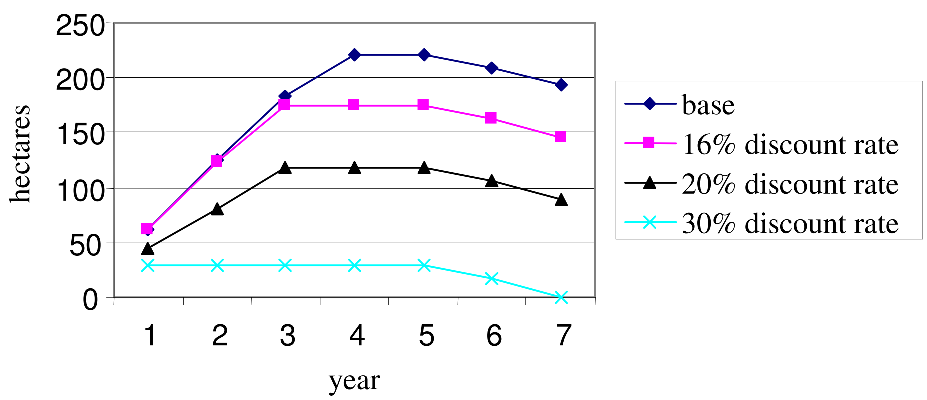


Figure A6. Simulated areas of eucalyptus plantations under different rates of discount in Maiaha



Nederlandse Samenvatting

De toename van de landbouwproductiviteit in Sub-Sahara-Afrika heeft geen gelijke tred gehouden met de groei van de bevolking. Om de groeiende bevolking toch te kunnen blijven voeden zijn steeds meer (marginale) gronden in gebruik genomen en de bestaande landbouwgronden worden steeds intensiever gebruikt. Traditionele methodes om de vruchtbaarheid van de grond te bewaren, zoals braakleggen van gronden, zijn door de noodzaak van het produceren van voedsel, in onbruik geraakt. Het gevolg hiervan is dat landbouwgronden op grote schaal degraderen en dat er op grote schaal erosie is ontstaan.

De problemen die zich voordoen in Sub-Sahara-Afrika (bodemdegradatie door een te grote bevolkingsdruk) kunnen in principe met de huidige beschikbare landbouwkennis opgelost worden. Er zijn diverse technische oplossingen voorhanden. De praktijk leert echter dat hoewel landbouwdeskundigen weten hoe de problemen opgelost zouden moeten worden dit niet gebeurt. Beschikbare technologie wordt niet geïmplementeerd en over het algemeen zien we dat de situatie steeds verder verslechtert.

In dit proefschrift wordt onderzocht wat hier de oorzaken van kunnen zijn. Het onderzoek richt zich op de situatie in de Hooglanden van Eritrea. Eritrea is een van de armste landen van Afrika en is voor een gedeelte van z'n voedselvoorziening afhankelijk van buitenlandse voedselhulp. Het grootste deel van de bevolking Eritrea is economisch afhankelijk van de landbouw. Verbetering van de productiviteit van de landbouwsector is daarom van wezenlijk belang voor de economische ontwikkeling en de armoedebestrijding.

Op dit ogenblik worden in de Hooglanden van Eritrea bijna alleen maar traditionele landbouwmethoden toegepast. Gewassen worden vooral verbouwd voor eigen voedselvoorziening, en ook voor verkoop op de markt. Een boerengezin houdt meestal ook wat vee, een of twee ossen voor het ploegen, enkele schapen en geiten en wat pluimvee. Als gevolg van een groot tekort aan brandhout, wordt de mest van de dieren vaak gedroogd en als brandstof gebruikt. Het beschikbare grasland voor vee is beperkt. Waren er vroeger veel bossen in de Hooglanden van Eritrea, door de bevolkingsdruk en de dertigjarige onafhankelijkheidsoorlog van 1961 – 1991, zijn bijna alle bossen verdwenen. Hout is een schaars goed geworden. De boeren staan voor moeilijke keuzes:

moeten ze het schaarse land voor gewasteelt, vee of bosbouw gebruiken? Kenmerkend voor de landbouw in de Hooglanden is de verdeling van land binnen een dorp, volgens het z.g. “Diesa system”. Huishoudens krijgen via een lotingsysteem stukken land van verschillende kwaliteit toegewezen, die zij gedurende een periode van zeven jaar mogen verbouwen. Daarna krijgt men weer voor zeven jaar (andere) stukken land toegewezen.

Het onderzoek omvat een diepgaande analyse van de boerenstrategieën in de Hooglanden, op het gebied van landbouw, veeteelt en bosbouw en hun onderlinge samenhang. Hierbij wordt de problematiek vanuit twee invalshoeken bestudeerd, aan de ene kant wordt er uitgebreid onderzoek gedaan in de rurale gemeenschappen zelf. Met behulp van interviews met boeren wordt onderzocht wat zij zelf vinden van hun situatie en wat zij zien als de belangrijkste redenen om nieuwe technieken wel of niet in te voeren. De gesprekken, interviews en observaties van het veldonderzoek werden uitgevoerd in drie representatieve dorpen in de Hooglanden. De resultaten van het veldonderzoek werden in belangrijke mate beïnvloed door bijzondere omstandigheden: ten tijde van het onderzoek waren bijna alle volwassen mannen opgeroepen in het leger vanwege oplaaiende grensconflicten met Ethiopië. Vanwege tekort aan arbeid heeft ook de landbouwsector hier enorm onder geleden.

Een tweede onderzoeksroute betreft het ontwikkelen van een wiskundig model, waarin de relaties tussen het socio-economisch systeem en de omgeving zijn gekwantificeerd. Het model is een mathematisch programmeringsmodel, waarmee boeren strategieën worden gesimuleerd. Met dit model kunnen de consequenties van de keuzes van de boeren m.b.t. tot het gebruik van bepaalde technologieën worden doorgerekend voor zowel het economische systeem (wat kost het, hoeveel arbeid is er mee gemoeid en wat levert het op) als voor de omgeving (wat betekent het gebruik van deze techniek voor erosie, ontbossing, bodemkwaliteit etc).

Voorbeelden van in het model opgenomen technologische verbeteringen zijn: het gebruik van kunstmest, het aanleggen van stenen muurtjes om erosie tegen te gaan, het gebruik van irrigatie, aanschaf van een tractor, aanplanten van bomen voor de brandhoutvoorziening, etc.

Door een combinatie van model berekeningen en van de resultaten van het onderzoek in de dorpen is nagegaan wat de perspectieven van verschillende technologieën zijn en wat belemmeringen zijn voor implementatie.

Enkele bevindingen en aanbevelingen

De landbouwsituatie in de Hooglanden is heel precair. De Hooglanden bestaan uit zeer ruig landschap met grote reliëfverschillen en met weinig en zeer onregelmatige neerslag. De bevolkingsdruk is hoog. De toepassing van traditionele landbouwmethodes en jarenlange oorlog en politieke onstabiliteit hebben geleid tot een lage productiviteit op de overwegend kleine landbouwbedrijven. Alleen door externe (voedsel) hulp zijn de huishoudens in dit gebied in staat te overleven.

Het onderzoek in dit proefschrift laat zien dat er diverse mogelijkheden zijn om de bestaande situatie te verbeteren. Het invoeren van de technologische vernieuwingen in de landbouwsystemen speelt daarbij een belangrijke rol. De financiële en sociale gevolgen van de implementatie van de diverse technologische vernieuwingen verschillen sterk per regio.
Dit betekent dat er per regio een aparte ontwikkelingsroute zou moeten ontwikkeld, die rekening houdt met de specifieke omstandigheden in de betreffende regio.

Een belangrijke vinding van dit onderzoek is dat het Diesa systeem de implementatie van nieuwe technieken belemmert. Dit geldt vooral voor technieken die zich pas over een langere periode terugbetalen zoals het aanleggen van dijkjes om de erosie tegen te gaan en het planten van bomen. Het verlengen van de huidige landgebruiksduur tot een periode langer dan zeven jaar zou een optie zijn om de boeren te bewegen meer tijd en geld in deze technieken te investeren.

Voor veel technologische vernieuwingen zijn investeringen nodig die de draagkracht van de bevolking te boven gaan. Investeringen voor waterpompen en aanschaf van landbouwmachines kunnen alleen met hulp van buitenaf plaatsvinden. Aan de andere kant blijkt dat dit niet voor kunstmest geldt. Daar wordt de invoering niet beperkt door de kosten maar meer door de onregelmatige neerslag in het gebied en de beperkte beschikbaarheid van kunstmest in de handel. De boeren lijken een hogere prijs te kunnen/willen betalen.
Op het moment wordt kunstmest gesubsidieerd. Op nationaal niveau legt deze subsidie een enorme druk op de begroting, waardoor het ook niet mogelijk is om voldoende kunstmest te subsidiëren, hierdoor wordt de beschikbaarheid negatief beïnvloedt.
Deze beperkte beschikbaarheid wordt door boeren juist als de beperkende factor gezien voor de implementatie van deze techniek. Het verbeteren van de beschikbaarheid eventueel in combinatie met een kredietsysteem voor kunstmest lijkt in dit geval een interessante oplossingsroute.

Het onderzoek geeft ook aan dat de economische verliezen als gevolg van erosie het grootst zijn op de landbouwgronden. Deze uitkomst heeft consequenties voor het inrichten van de 'Soil and Water Conservation' (SWC) projecten. Deze projecten richten zich op het moment sterk op erosie-bestrijding op de niet voor landbouw in gebruik zijnde hellingen. De inzet van arbeid op deze hellingen gaat vaak ten koste van de inzet voor het onderhoud van de landbouwgronden. Hierdoor neemt de erosie vanaf de landbouwbouwgronden toe, hetgeen leidt tot lagere opbrengsten. De analyse van deze situatie in dit onderzoek laat zien, dat het voor de boeren economisch meer rendabel is om de beschikbare arbeid in eerste instantie in te zetten op het tegengaan van de erosie op de landbouwgronden.

De bestaande herbebossingstrategieën zijn ook met behulp van het model geanalyseerd. Er zijn twee opties om te herbebossen. De ene is de natuurlijke regeneratie van de inheemse soorten door landbouw en weidegrond uit het voedsel-productie-systeem te halen. Dit systeem vraagt nauwelijks investeringen maar de 'opportunity costs' zijn hoog (verlies van de productie van die gronden: gewas en vee). De andere mogelijkheid betreft het aanplanten van snelgroeiende bomen zoals Eucalyptus. Dit systeem vraagt investeringen in arbeid en geld, maar heeft een veel hoger rendement. In de dichtbevolkte Hooglanden, waar men geen grond kan missen, lijkt de aanplant van Eucalyptus de grootste kans van slagen te hebben. Er wordt daarom voorgesteld om in de dichtbevolkte gebieden waar de natuurlijke bossystemen toch al zijn verdwenen, de herbebossingsprogramma's te richten op de aanplant van Eucalyptus.
Het beschermen van de inheemse bossystemen, wat een van de milieudoelen van de nationale regering is, zou het best kunnen plaatsvinden in de dunbevolkte streken. In deze gebieden komen deze ecosystemen nog voor. Voor de bescherming van deze natuurlijke bossen is het van belang dat de houtkap beperkt wordt. Dit kan worden bewerkstelligd door de introductie van meer energie-efficiënte houtovens, de introductie van snelgroeiend hout voor de brandhoutvoorziening en bevorderen van het gebruik van andere energiebronnen door de huishoudens.

Tot slot moet worden opgemerkt dat de hierboven beschreven mogelijkheden om de landbouw situatie in de Hooglanden te verbeteren alleen ten uitvoer kunnen worden gebracht als er een eind komt aan de politieke instabiliteit in Eritrea.
De terugkeer van de jonge boeren naar hun boerderijen is van essentieel belang voor het verbeteren van de landbouwomstandigheden in dit gebied en het verbeteren van de levensomstandigheden van de rurale bevolking.

Stellingen

Poverty and Natural Resource Management in the Central Highlands of Eritrea

Bereket Araya

1. We do not inherit the earth from our ancestors. We borrow it from our children. (David Brower, founder of Friends of the Earth)

2. At the heart of rural development is agricultural production. Whatever is done to promote rural development through non-agricultural investments, agriculture has to be the base of any rural strategy. (MOA, 2002)

3. Much of the environmental degradation in developing countries occurs in less-favored areas [such as the Central Highlands of Eritrea]. This degradation is intimately linked to low land productivity, poverty and food insecurity. (Ruben et al., 2003)

4. While population growth may induce a process of agricultural intensification, this process may fail to take place due to economic, institutional and policy conditions. (This thesis p. 13)

5. A thorough understanding of farmers' goals, their production practices and constraints is needed to ensure that technological and policy interventions are successful to generate the desired outcome. There are no short-cuts to this (Pandey, 2001).

6. Farmers in Eritrean Highlands are aware that the quality of their life highly depends on the quality of the natural resources. Thus an over use of the resources is not out of choice but out of necessity.

7. Ekhli ay kab baytan kab bayto, roughly translated as "good harvest is rather the result of good governance than of good land". (Old Eritrean Proverb)

8. Despite many criticisms the *diesa* system (communal land ownership) is still highly regarded by the farmers in the Central Highlands of Eritrea.

9. The *diesa* system has its own advantages and disadvantages. Changing the system immediately and entirely is neither practical nor desirable. Nevertheless, it is important that some improvements are made. (This thesis p. 213)

10. The relationships among the countries in the Horn of Africa are beset by political and military conflicts. Nevertheless, the welfare of the people and the development of the region are contingent on a peaceful coexistence and mutual cooperation of the countries.

11. A good bike lock is expensive in Groningen but it is worth the expenditure.